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SORBENT INJECTION FOR SO_2 CONTROL
A. Sulphur Capture by Various Sorbents
B. Humidification

Report No. 88-63-K

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ABSTRACT

Sulphur capture by in-furnace injection of calcium-based sorbents has been studied at Ontario Hydro's 640 MJ/h Combustion Research Facility under conditions simulating full scale operation. These studies are an important component of the Corporation's acid gas control program. The study is aimed at quantifying the effects of process parameters on SO_2 capture, sorbent utilization, waste characteristics and ESP performance. Sorbent types tested include: two calcitic limestones, a hydrated lime and a dolomite. Injection temperature, residence time, sorbent addition rate and particle size have been optimized to maximize SO_2 capture and sorbent utilization and to minimize the impact on particulate removal by the ESP. Under optimized operating conditions while burning a 1.7% S bituminous coal up to 43% SO_2 can be removed from flue gases using a nonporous, 56% using a porous calcitic limestone, 63% using a hydrated lime and 51% using a dolomite, in good agreement with full scale test results. The resulting waste is finer than the ash alone. The solids loading is about 200% greater with sorbent injection, and ash resistivities are up to three to four orders of magnitude higher than that of the coal ash. ESP performance deteriorated by about 2-16% in efficiency

depending upon the sorbent used. Humidification of sorbent injection waste upstream of the electrostatic precipitator enhanced SO_2 capture by about 6% for hydrated lime, 18% for limestone and 7% for dolomite injection, bringing the total SO_2 capture to 67%, 61% and 51% respectively. Humidification reduced the resistivity of the waste from about 10^{11}-10^{12} to 10^{8} ohm.cm and improved the efficiency of the ESP.

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EXECUTIVE SUMMARY

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Humidification of sorbent injection flue gases to enhance SO_2 capture, sorbent utilization and ESP performance was also carried out upstream of the ESP while burning a 1.7% S eastern US bituminous coal and a 50-50 Western Canadian-US coal blend.

Under optimized operating conditions (Ca/S = 2.5-3.0, sorbent mass median diameter 3.9 - 8.6 μm, injection temperature 875 - 1100°C and simulating the Lakeview TGS quenching rate) up to 63% SO_2 can be removed from flue gases by hydrated lime, 56% by Pt. Anne limestone, 51% by dolomite and 43% by Beachville limestone. The corresponding sorbent utilizations are: 25%, 19%, 17% and 14%. By increasing residence time in the furnace by simulating Lambton quenching rate, sulphur capture was improved from 43% to 52% while injecting the Beachville limestone but only from 65 to 70% in the case of lime injection. Calcium utilization increased from 14% to 17% and 26% to 28% respectively.

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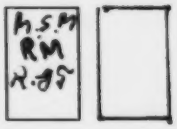
The process produces a waste which is finer and about 2.2 times as much as the baseline coal. A 2 to 3 fold increase in dust emission was observed causing a drop in ESP efficiency by about 2% for limestone and 16% for hydrated lime. Ash resistivities increased by 3 to 4 orders of magnitude from baseline levels of 10^8 ohm.cm.

Humidification of sorbent injection flue gases to a 20-25°F approach to adiabatic saturation produced an incremental SO_2 capture of 18% for Beachville limestone, 6% for hydrated lime and 7% for dolomite corresponding to a total of 61% for limestone, 67% for hydrated lime and 51% for dolomite. Ash resistivity was lowered by 3 to 4 orders of magnitude and the efficiency of the ESP was improved.

Slagging does not appear to be a problem and the soft deposits found on the furnace walls and heat exchanger surfaces were easily removed, suggesting that conventional soot blowing may suffice for full scale operation except that the frequency of soot blowing may have to increase.



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To Dr. W.R. Effer
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SORBENT INJECTION FOR SO_2 CONTROL

A. SULPHUR CAPTURE BY VARIOUS SORBENTS
B. HUMIDIFICATION

1.0 INTRODUCTION

Ontario Hydro is committed to the reduction of the level of acid gas emissions from its coal burning plants. The main pollutants of concern are sulphur dioxide and nitrogen oxides. In December, 1985, the Ontario Government announced stricter acid gas emission limits for Ontario industries and Ontario Hydro is limited to 430 000 tonnes/ year starting in 1986 and 215 000 tonnes/year starting in 1994. Four nuclear units coming into service will reduce coal burns and acid gas emissions well below regulated limits into the early 1990's. In the 1990's uncertainties in load forecasts and the demand/supply options indicate that wide variation in coal burns are possible and various control technologies will be required/1/.

In order to maintain flexibility to meet future demands for electricity and comply with tightening acid gas regulations it is likely that Ontario Hydro will have to retrofit some form of flue gas desulphurization (FGD) equipment on its coal-fired plants by mid- to late-1990's. To achieve these objectives studies are being conducted to select technologies and obtain government approval for the installation of appropriate FGD systems at selected coal -fired stations. In order to satisfy requirements of the Ontario Environmental Assessment Act, a Program Environmental Assessment (PEA) is being prepared that will request approval for planning, design, construction, operation/maintenance and decommissioning of all FGD and associated facilities required over a 20-year period.

In parallel with the PEA, Ontario Hydro is carrying out FGD process evaluation and selection studies designed to identify the most appropriate technologies for use at its coal-fired stations. These studies consist of conceptual engineering and research and development activities. The processes that are being considered for initial application can be divided into two categories: high capital cost, high removal efficiency and low capital cost, low efficiency systems. The wet limestone slurry, limestone dual alkali, lime spray drier fit into the first category. The sorbent injection technology (in-furnace, in-duct and related improved technologies) fits into the second

category. Sorbent injection has a definite cost advantage for boilers with short remaining life. It is ideally suited for retrofit application and requires a shorter lead time for installation than wet scrubbers.

A major research program aimed at improving the performance and cost effectiveness of sorbent injection is in progress at the Research Division in support of the full scale demonstration of the technology at Lakeview TGS/2/.

The various phases of this multi-year program are shown in Table 1. The first phase of the program was previously reported/3,4/. This report summarizes the second phase, where methods for improving SO_2 capture and sorbent utilization by increasing residence time in the furnace, using more reactive sorbents such as dolomite, hydrated and pressure hydrated lime and humidification were studied. Full-scale data obtained at Lakeview TGS were compared to pilot scale test results. Ash characteristics and their impact on the furnace and ESP are also discussed.

TABLE 1 DEVELOPMENT OF SORBENT INJECTION FOR SO_2 CONTROL

PHASE	PROGRAM DESCRIPTION	STATUS OF R&D
I	Application of the technology to Lakeview TGS	Complete(3-6)
II	a. Application of the technology to Lambton TGS	Complete
	b. Comparison of limestone, hydrated lime and dolomite	Complete. Presented at the Conference on Effects of Coal Quality on Power Plants, Oct 13-15, 1987, Atlanta, Georgia(7,8)
III	a. Sorbent injection - humidification	Complete (7-8)
	b. Sorbent slurry injection	Sept 1987 - Jun 1988
	c. Sorbent injection - waste activation and recycling	Sept 1988 - Jun 1989
IV	Induct injection of hydrated lime and LI waste	Apr 1989
V	Reburning with limestone injection	Probably May 1988 - Apr 1989

2.0 IN-FURNACE SORBENT INJECTION

The process involves the injection of dry calcium-based sorbents such as limestone, hydrated lime or dolomite directly into the furnace. At the high furnace temperatures the sorbent is flash-calcined to lime according to the following reactions:

$$CaCO_3 \xrightarrow[500\text{-}900°C]{} CaO(s) + CO_2(g)$$

$$CaCO_3 \xrightarrow[500\text{-}900°C]{} CaO(s) + MgO(s) + 2CO_2(g)$$

(MgO_3: 300-700°C)

$$Ca(OH)_2 \xrightarrow[200\text{-}550°C]{} CaO(s) + H_2O(g)$$

In the case of limestone, structural rearrangement takes place because the crystal structure of the carbonate (rhombohedral) differs from that of the oxide (cubic). During this process, localized crystallites, or grains are formed at various sites with a pore structure between them. The particles heat up very rapidly (< 50 ms) after mixing with the hot gas stream and at typical combustion temperatures the overall calcination process appears to be essentially complete in less than 200 ms. The calcination conditions, particularly temperature and CO_2 partial pressure, influence the ultimate porosity and grain size. Extended exposure to high temperature often causes the grains to coalesce (sinter) because the highly mobile oxide units quickly fill in the gaps where grain boundaries, or contact points occur. This results in larger grains, with lower surface area.

Once the sorbent particle is oxidized to CaO, it can react with the available sulphur species to form calcium sulphate. The overall reaction for sulphation is:

$$CaO(s) + SO_2(g) + 1/2O_2(g) \rightarrow CaSO_4(s)$$

Under oxidizing conditions the heterogeneous sulphation reaction is the result of a four-step process:

- Diffusion of the gaseous reactants to the particle surface;
- Diffusion through the pores to the particle's interior;
- Diffusion through the calcium sulphate product layer, and
- Reaction at the product/reactant interface.

Thus, the overall reactivity of the sorbent will depend on the relative importance of these resistances and on the specific surface area of the sorbent, available for reaction. Controlling resistances and internal sorbent structure may also vary with time, further complicating the reaction mechanism.

The $CaSO_4$ and unreacted CaO are collected with the fly ash in the electrostatic precipitator (ESP).

The sorbent injection process has been studied in pilot- and plant-scale in Germany, Japan, the United States and Canada. A full scale demonstration of limestone and hydrated lime injection has been completed at the 300 MW Unit No 4 at Ontario Hydro's Lakeview Thermal Generating Station (LV TGS)/2/. The tests are backed by extensive bench and pilot scale studies carried out by Chemical Research Department/3-7/. These studies are aimed at (a) improving our understanding of the fundamental aspects of sorbent-SO_2 reaction chemistry, (b) quantifying the effect of a number of process parameters on in-furnace sulphur removal, sorbent utilization, ESP performance, waste characteristics and disposal, and optimizing system performance to minimize cost.

In the first phase of the pilot scale studies, conducted at the Division's 640 MJ/h (6.1×10^5 BTU/h) Combustion Research Facility the effect of the most important process variables such as injection temperature, sorbent particle size and addition rate on SO_2 capture, sorbent utilization, ash characteristics and ESP performance were evaluated, when burning a 1.7% S US bituminous coal and injecting a local calcitic limestone into the furnace. The studies indicated that under optimized operating conditions, simulating LV TGS Unit 4 quenching rate (injection temperature - 1100°C (2012°F), sorbent mass median diameter - 8.6 μm, residence time approx 0.6 s, Ca/S ratio of 2.5 to 3), up to 43% SO_2 can be removed from the flue gases. The corresponding sorbent utilization is 14%. The process produces a finer waste and solids loading with limestone injection is about 200% greater than with coal alone. The resistivity of the sorbent injection ash is up to three orders of magnitude higher than that of coal ash. The high solids loading and increased resistivity have shown adverse effects on ESP performance. Due to the high levels of calcium oxide in the waste an exothermic reaction and a plaster-like setting takes place on addition of water, necessitating great care in handling and disposal/8/.

3.0 IMPROVING PROCESS PERFORMANCE

The results of the in-house R&D studies and work conducted elsewhere indicate that SO_2 capture by boiler limestone and lime injection is limited to 45-65% primarily due to the temperature-time profile of typical utility boilers. Needless to say, the higher the SO_2 removal and the better the sorbent utilization achieved by sorbent injection, the lower the impact on ESP performance and waste disposal, and the greater its potential value.

Many studies are underway, mostly in the US, to improve process performance through low cost modifications of sorbent properties. These techniques include: sorbent precalcination, use of promoters, pressure hydration and precipitation of lime from alcohol solution. Unfortunately none of these approaches are promising/9/. Sulphation experiments with high surface area sorbents such as pressure hydrated lime and limes precipitated from alcohol solutions have shown that these materials perform only marginally better than regular hydrated lime. Promoters expected to enhance SO_2 capture and sorbent utilization also did not show significant improvements.

Precalcination, a technique to produce porous and reactive sorbents, was also not effective. Precalcines, although porous when produced, lost their reactivity as a result of fast sintering during sulphation experiments at 1000°C. In the furnace there was no difference in the performance of high-surface area sorbents, precalcines and "raw" sorbents.

The schematic diagram of a few modified sorbent injection techniques, which indicated promise to improve SO_2 capture and sorbent utilization/10-15/ is shown in Figure 1.

A. **Sorbent Injection with Humidification**

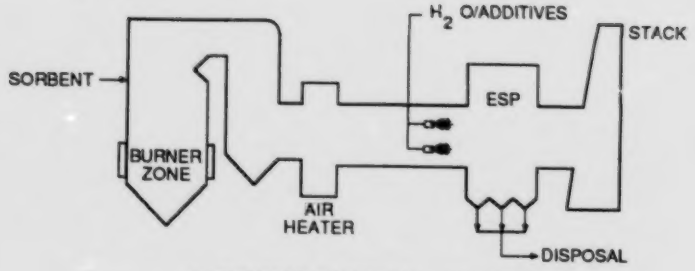
This process involves humidification and possibly additive injection upstream of the ESP to achieve additional SO_2 removal, improve sorbent utilization and ESP performance while the furnace is operating with limestone injection. In the boiler, injected limestone is calcined and SO_2 is captured by the calcine. Since calcium utilization is low, the ash contains significant amounts of unreacted CaO. Flue gas humidification, the atomization and evaporation of water droplets in the flue gas duct, activates the unreacted CaO and utilizes it for additional SO_2 capture in the humidifier and ESP. The increase in sorbent utilization can significantly improve SO_2 control economics, compared to furnace sorbent injection without humidification. ESP performance is impaired during furnace sorbent injection because of the substantial increases in particulate loadings and ash resistivity. Humidification can also help to overcome the poor ESP performance caused by the injection of calcium-based sorbents. Humidification lowers the ash resistivity, flue gas volumes and temperatures/10,11/.

B. **Sorbent Slurry Injection**

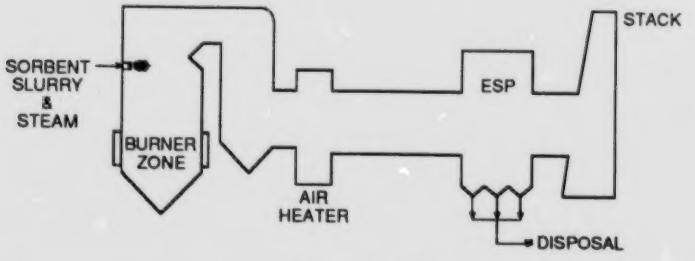
In this process an aqueous spray of Ca-based sorbent is injected into the combustion chamber at temperatures ranging between 990 to 1200°C. This technique assures improved distribution and mixing of the sorbent with the gas flow, prevents sorbent deactivation and allows for sufficient residence time, at favourable temperatures for the reaction between SO_2 and CaO to be efficiently completed/15/. The schematic diagram of the process is shown in Figure 1B.

The following steps are involved in the process:

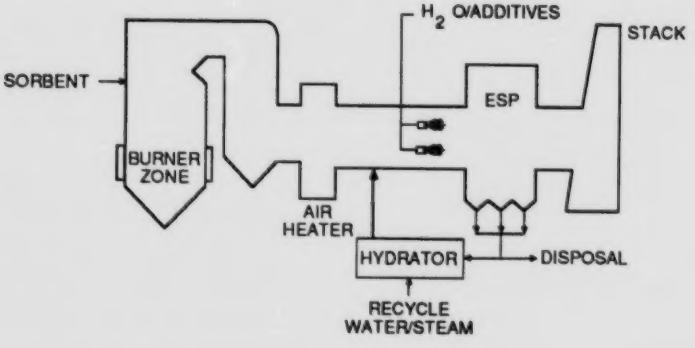
- Sorbent-water atomization and intimate mixing with flue gas;
- Water droplets evaporation;
- Particle disintegration due to increased vapour pressure in the pore structure;
- Calcination resulting in additional fragmentation, development of high surface area and pore structure;
- Sulphur capture by the porous reactive sorbent in a favourable thermal environment.



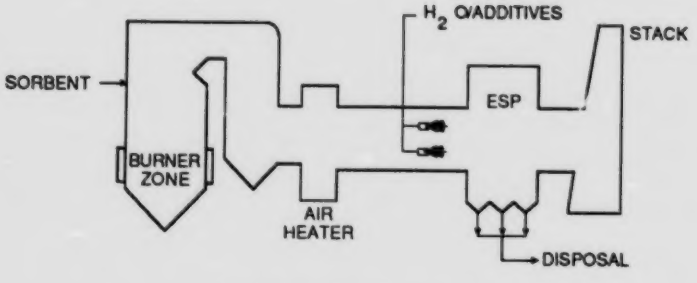
A. FURNACE INJECTION - HUMIDIFICATION



B. SORBENT SLURRY INJECTION



C. FURNACE INJECTION - WASTE ACTIVATION & RECYCLING



D. INDUCT SORBENT - HUMIDIFICATION

FIGURE 1

OPTIONS TO IMPROVE SORBENT INJECTION

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As the water evaporates the sorbent is calcined and forms very fine and well dispersed particles, ready to react with SO_2 in a temperature range of 990-1200°C. At these temperatures sintering, loss of calcine surface area and reactivity is very slow.

C. **Furnace Injection - Waste Activation and Recycling**

This technique involves the activation and re-injection of waste after activation from in-furnace injection of limestone or lime into the furnace or the duct upstream of the ESP. Preliminary data indicate that the waste can be reactivated by hydration or steam processing/16/. Waste activation and recycling offer economic benefits because the waste from furnace injection becomes a low-cost sorbent for in-furnace and/or in-duct injection.

D. **Low Temperature Sorbent Injection**

Bench- and pilot-scale tests of injection of hydrated lime into the duct upstream of the precipitator at about 150°C, and into the economizer at temperatures between 430-650C/12-13/ have shown significant potential for removing SO_2 from flue gas streams. The capital requirements for these techniques are low because the duct work upstream of the precipitator or in the economizer region provide the reactor for SO_2 capture. The spent sorbent is removed along with the coal ash in the ESP.

For use in a plant equipped with an ESP, the technology requires a highly reactive sorbent to achieve acceptable SO_2 removal and sorbent utilization. Laboratory studies indicate that the sorbent reactivity required for the low temperature injection is about two orders of magnitude greater than that of hydrated lime. High surface area hydrated limes, promoted with an additive, appear to the be most effective.

This report summarizes the result of the pilot-scale studies aimed at improving SO_2 capture and sorbent utilization by increasing residence time in the furnace, using more reactive sorbents such as dolomite, hydrated and pressure hydrated lime and humidifying the waste. Emphasis was placed on ash characteristics and the impact of sorbent injection with and without humidification on the furnace and ESP.

4.0 EXPERIMENTAL

4.1 Combustion Research Facility

The study was conducted at Ontario Hydro's Combustion Research Facility (CRF), designed for a maximum coal feed rate of about 20 kg/h US bituminous coal at a firing rate of 640 MJ/h (Figure 2). The furnace is a refractory-lined cylindrical chamber, fully equipped for monitoring gas and wall temperatures. There are multiple ports for flame observation and for insertion of solid sampling probes. The pulverized coal is delivered down-draft to the

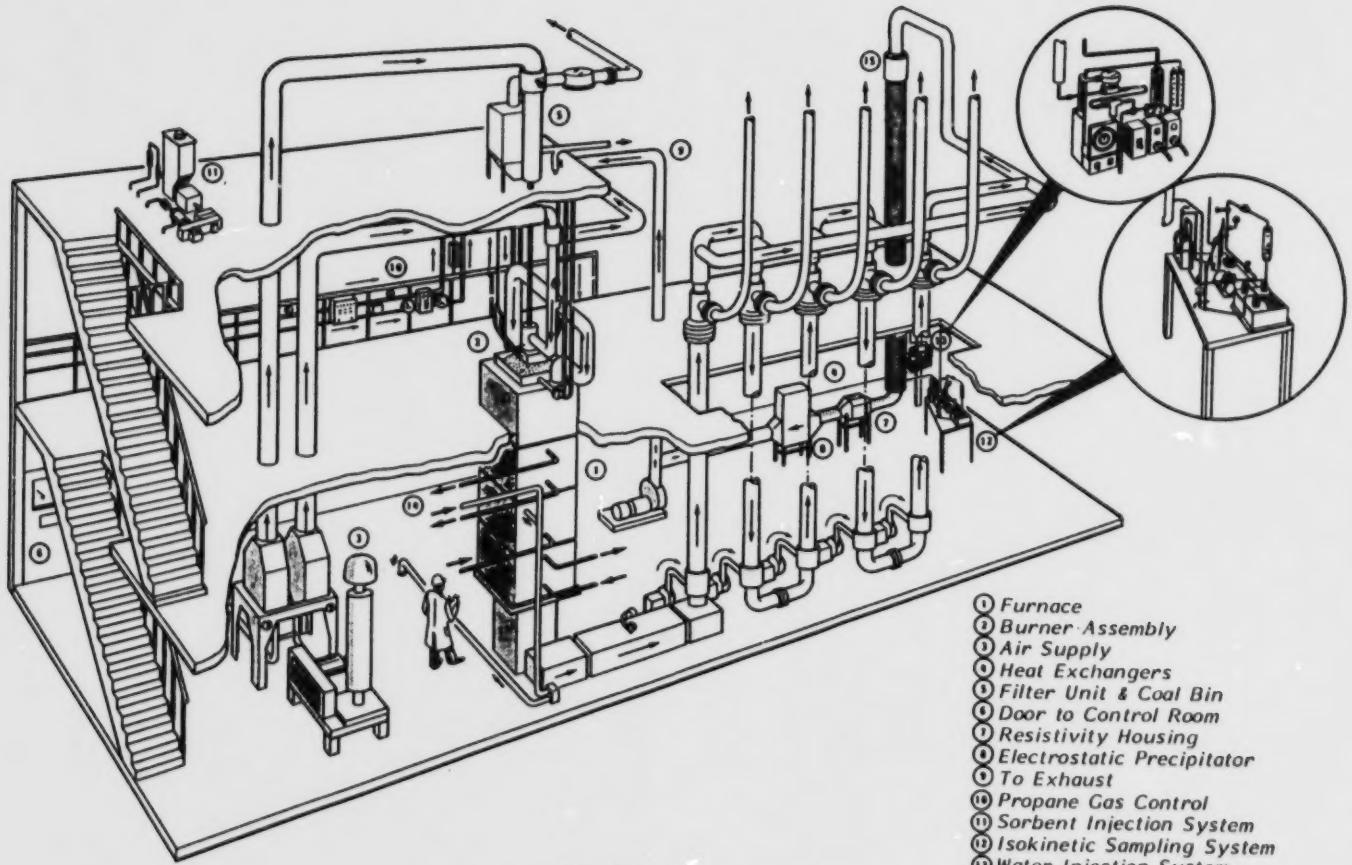

FIGURE 2

COMBUSTION RESEARCH FACILITY

169780 RD

burner with the combustion air which can be electrically preheated to temperatures up to 350°C (662°C). Gas burners on each side of the coal burner are used to heat the furnace to operating temperatures before beginning to feed the coal.

The coal burner, designed and constructed by Research Division staff, is equipped with a vortex generator and four air vanes to assure good mixing and adequate residence time of the fuel-air mixture in the combustion zone. The combustion gases in the furnace are cooled by water and/or air circulating in a cylindrical Inconel jacket around the furnace. This cooling system is equipped with temperature sensors and flow meters to control furnace quenching rates.

The combustion gases leaving the furnace are further cooled by a series of air-cooled heat exchangers prior to entering the resistivity probe housing and ESP. The ESP consists of a cubic stainless steel chamber, and is equipped with two sets of interchangeable cells. One set has an 11-plate electrode with 2.5 cm (1 in) spacing, the other a 5-plate electrode with 5 cm (2 in) spacing. The design specific collection areas (SCA, $m^2/m^3/s$) for the two sets of cells are 39 (0.2 ft^2/cfm) and 17 (0.09 ft^2/cfm) respectively for base line firing conditions using a high volatile US bituminous coal.

The CRF instrumentation permits system temperatures, and flue gas compositions (O_2, CO_2, CO, SO_2 and NO_x) to be monitored continuously. Gas temperatures in the furnace were measured with a suction pyrometer and flame temperatures with an optical pyrometer. Flow rates and pressures are measured by flow meters and manometers. All measuring and monitoring systems are linked to a computerized data acquisition system. Particulate mass loading in the flue gas before and after the ESP is measured with an isokinetic sampling system. In-situ resistivity is measured with a point-plane resistivity probe situated in the resistivity probe housing.

The sorbent injection system consists of sorbent injection ports installed at five locations along the length of the furnace and a storage and feeding system for sorbents and additives. The sorbent is injected into the furnace by a spray nozzle. Detailed description of the facility and its sub-systems is given in Reference 4.

4.2 Humidification Chamber

Humidification of flue gases was carried out in a cylindrical humidification duct 19 cm ID (7.5 in) and 5.8 m (19 ft) long. The chamber is equipped with three ports for water injection nozzles and five ports for inserting thermocouples to measure dry-bulb/wet-bulb temperatures and gas drying times. Residence times in the chamber could be varied between 0.4 - 3 s. Flue gas at about 300°F enters at the top of the chamber with a velocity of about 1.8 m/s (6 ft/s). Water is injected by a single spray nozzle, radially centered and upon complete evaporation it reduces the flue gas temperature to a 20 to 25°F approach to adiabatic saturation. The chamber is shown in Figure 3.

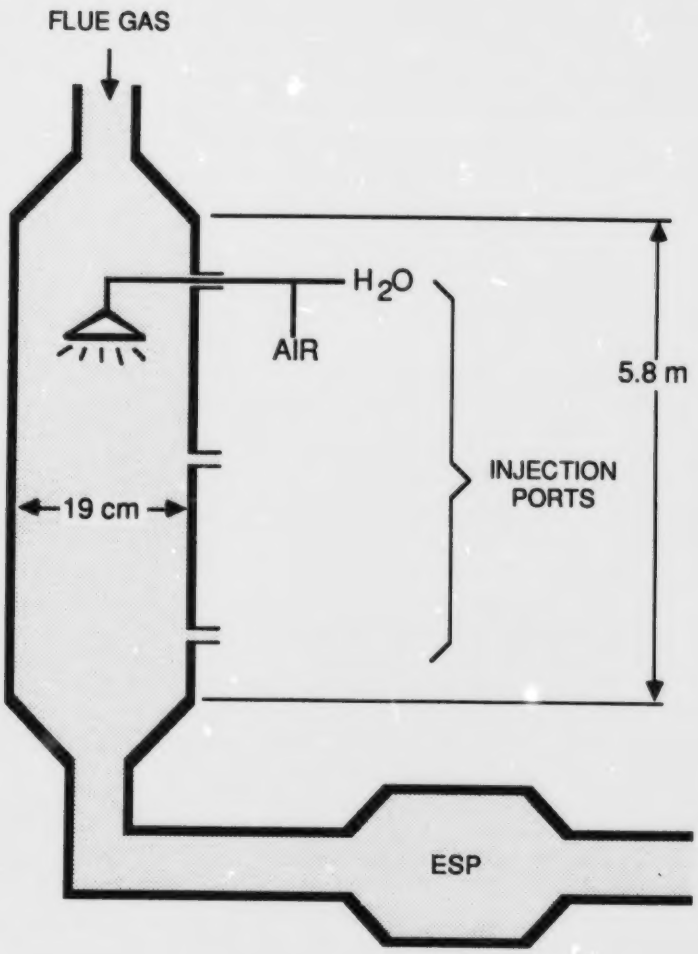

FIGURE 3

HUMIDIFICATION CHAMBER

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4.3 Sampling and Analysis

The various sampling systems and the analytical methods used are described in Reference 4.

(a) **Coal Analysis**

A high volatile medium sulphur eastern US bituminous coal from Lakeview TGS and an eastern US/western Canadian coal blend from Nanticoke TGS were used in the study. Ultimate and proximate, analyses and particle size distribution of these coals are given in Table 2. The particle size distribution is plotted in Figure 4.

(b) **Sorbent Analysis**

The sorbents tested include a calcitic limestone and a hydrated lime from Beachville, Pt. Anne calcitic limestone from east of Belleville, and E.C. King dolomitic stone. The chemical and physical properties of the sorbents are shown in Table 3.

4.4 Procedures

The combustor was heated with propane gas overnight at a rate of about 240 MJ/h, achieving temperatures in the range of 900 to 1000 °C on the morning of the planned test. The gas was then boosted to approximately 350 MJ/h where temperatures in the range of 1200 to 1250 °C were obtained. Upon attaining the desired quench rate, the switch from propane to coal was made. Temperature-time and radial profiles of flue gases are shown in Figure 5. Temperatures were measured with a suction pyrometer.

After steady state was achieved with the baseline coal, pneumatic injection of the sorbent into the furnace at specified locations (I_0 to I_4) with an adjustable screw feeder was initiated. Temperature-time and radial profiles of flue gases under conditions simulating Lakeview and Lambton TGS thermal profile are shown in Figure 5. Data collected during each test include system temperatures and pressures, sorbent-feed rates, flue gas constituents concentrations (CO_2, O_2, CO, SO_2 and NO_x) and in-situ ash resistivities. Coal, sorbent feed and fly ash samples were collected during the tests and analyzed.

5.0 RESULTS AND DISCUSSION

5.1 Comparison of Sorbents

Sorbent composition and physical properties are one of the most important factors in determining overall capture performance. The parameters that were found to affect sulphur capture efficiency include:

- sorbent properties that affect the degree of porosity, particle size and surface area after calcination;
- temperature at the point of injection;
- residence time in the sulphation window, and
- Ca/S ratio.

TABLE 2

COAL ANALYSIS

PROXIMATE ANALYSIS, g/kg
(as received)

	US Coal	W. Can - US Coal Blend
Moisture	14	32
Ash	80	99
Volatile Matter	357	321
Fixed Carbon	548	548

ULTIMATE ANALYSIS, g/kg
(dry basis)

	US Coal	W. Can - US Coal Blend
O	74	101
C	756	751
H	57	47
N	16	11
S	17	14
Ash	80	71
Heating value MJ/kg	32	29

PARTICLE SIZE DISTRIBUTION

	Cumulative % Passing	
Sieve Opening μm	US Coal	W. Can - US Coal Blend
150	100	100
106	93	98
75	73	84
63	59	76
53	56	63
44	51	19
<44		

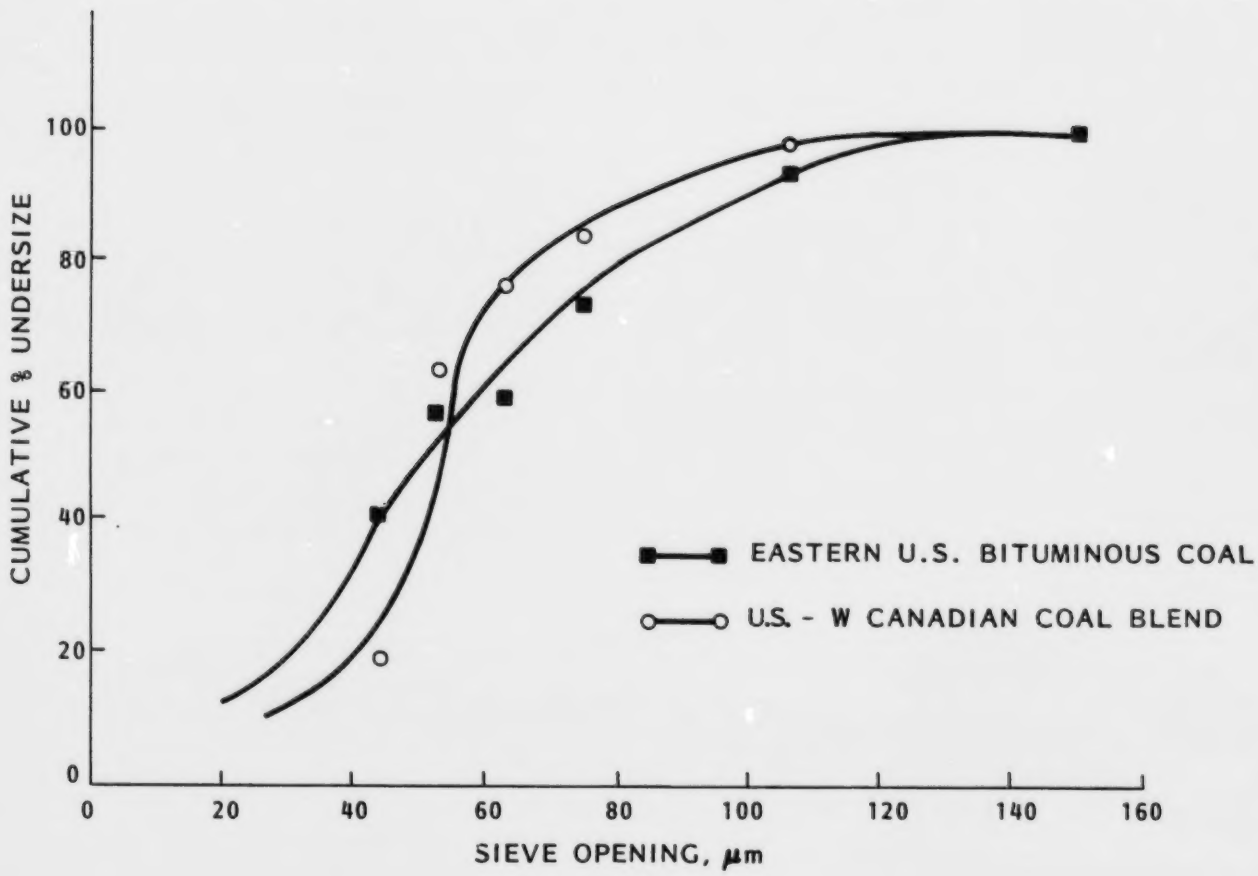


FIGURE 4
PARTICLE SIZE DISTRIBUTION OF U.S. AND
U.S.- WESTERN CANADIAN COAL BLEND

TABLE 3

CHEMICAL AND PHYSICAL PROPERTIES OF SORBENTS

	BEACHVILLE LIMESTONE	PT. ANNE LIMESTONE	E.C. KING DOLOMITE	BEACHVILLE HYDRATED LIME
Li_2O, g/kg	<0.03	-	-	0.002
Na_2O	0.03	0.1	0.4	0.3
K_2O	0.6	0.5	<1.0	<0.05
MgO	8.0	4.8	212.1	7.6
CaO	524.0	535.4	300.9	141.0
Fe_2O_3	0.1	2.1	2.3	1.5
Al_2O_3	22.0	4.3	1.0	2.2
SiO_2	<12.0	21.0	7.9	5.1
$Ca(OH)_2$				788.0
LOI	434.0		461.0	
BET area, m^2/g	1.3	2.9	0.6	12.6
MMD, μm	8.6	3.9	33.0	8.2
ρ, g/cm^3	2.6	2.3	2.5	2.1
POROSITY, %	17.0	55.0	42.0	26.4

Significant variability in the reactivity of various sorbents has been observed. Hydrated limes have been found to be superior sorbents relative to the parent carbonates. Dolomites show higher reactivity than calcite stones. Also, sorbents with smaller mean particle size are generally more reactive/17/.

The reactivity of hydrated lime is a function of its surface area and porosity, which in turn are determined by the physical and chemical characteristics of the parent quicklime and the conditions of the hydration process. Apparently pressure slaking - an expensive process - did not produce a better sorbent than atmospheric hydration. Therefore only very few tests were conducted with this sorbent. The superiority of the hydrates relative to the carbonates can be attributed to the following:

- Dehydration occurs significantly more rapidly than CO_2 evolution so that the time available for sulphation after completion of the calcination process, is longer with hydrates than with carbonates.
- The dehydration process generally reduces the particle size and the SO_2 diffusion resistance and enhances capture.
- Hydrates have a much higher surface area than carbonates (13 m^2/g vs 1-3 m^2/g).

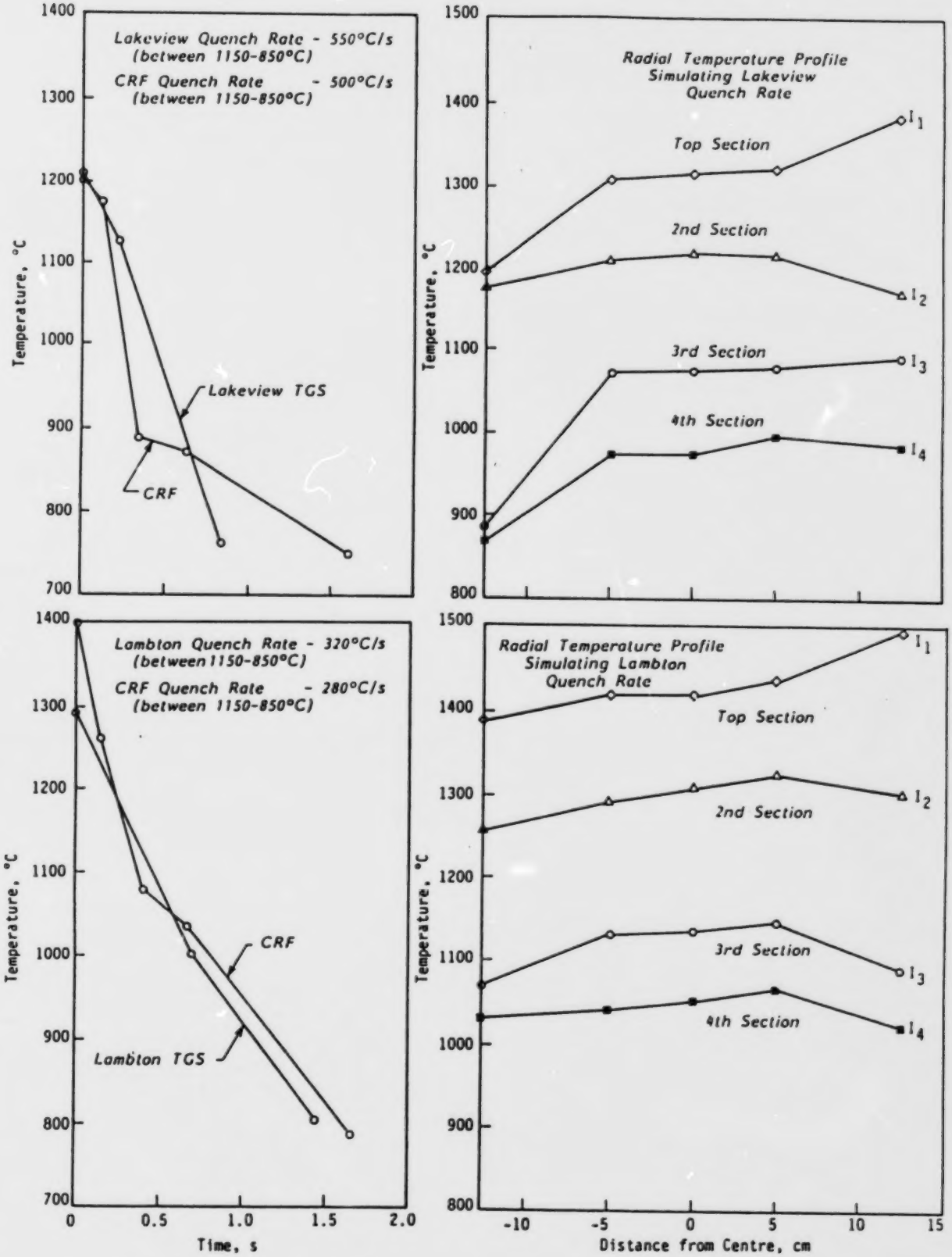


FIGURE 5 TEMPERATURE-TIME AND RADIAL PROFILES OF FLUE GASES

Dolomitic sorbents are known to be very effective in achieving sulphur capture. Literature data suggest/18/ that magnesium does not react with SO_2 to form magnesium sulphate. Apparently the role of magnesium is that of a promoter: it enhances calcine surface area production by dehydration of $Mg(OH)_2$, product layer diffusion and initial chemisorption of sulphur species.

The reactivity of four sorbents of interest to Ontario Hydro were investigated under carefully controlled conditions at the pilot scale. The sorbents studied have included Beachville limestone and hydrated lime, a Pt. Anne limestone, and E.C. King dolomite. Chemical composition and physical characteristics of these materials are shown in Table 3.

The effect of variables on sulphur capture, such as temperature, and Ca/S ratio was evaluated for all four sorbents, while the effect of residence time was evaluated only for limestone and hydrated lime. In these experiments the sorbents were injected into the furnace at various locations corresponding to wall temperatures ranging from 1375 to 875°C, (2507 - 1607°F) at Ca/S ratios of 1.5 to 3. The effect of residence time was studied by varying furnace quenching rate at otherwise constant operating conditions. The results are summarized in Table 4.

To correlate sulphur capture to the most important operating variables, statistical analysis of the pilot scale data was carried out using PROC GLM of SAS. The response surface diagrams developed for the in-furnace sorbent injection experiments have the following general form:

$$S = C_o T^{\alpha} \exp(\beta T + \gamma T/R^{\delta})$$

where: S = Percent sulphur capture; T = Injection temperature; R = Calcium sulphur mole ratio; C_o, α, β, γ and δ are constants

The constants for Beachville limestore and hydrated lime injection at various furnace quenching rates are shown below:

Quenching Rate, °C/s	Limestone	Hydrated Lime
500 (Lakeview TGS)	$C_o = e^{-81.15}$ $\alpha = 14.42$ $\beta = -0.01442$ $\gamma = -0.00254$ $\delta = 2.0$ $R^2 = 0.95$	$C_o = e^{-34.40}$ $\alpha = 6.60$ $\beta = -0.00692$ $\gamma = -0.00349$ $\delta = 4.0$ $R^2 = 0.91$
280 (Lambton TGS)	$C_o = e^{-117.47}$ $\alpha = 20.21$ $\beta = -0.01814$ $\gamma = -0.00227$ $\delta = 2.0$ $R^2 = 0.90$	$C_o = e^{-232.14}$ $\alpha = 39.35$ $\beta = -0.0356$ $\gamma = -0.00695$ $\delta = 6.0$ $R^2 = 0.96$

TABLE 4

SULPHUR CAPTURE BY IN-FURNACE INJECTION OF VARIOUS SORBENTS

COAL TYPE	SORBENT TYPE	SORBENT MMD, μm	SORBENT Ca/S RATIO	INJECTION TEMP °C	RESIDENCE TIME, s	% SO_2 CAPTURE	% SORBENT UTILIZATION
Eastern U.S. Bituminous	Beachville Limestone	8.6	3.0	1300	>0.7	23	8
			3.0	1100	0.6	43	14
			3.0	875	0.3	39	13
	Beachville Hydrated Lime	8.2	2.5	1100	0.6	63	25
			3.0	875	0.3	65	22
			2.5	875	0.3	61	24
			2.0	875	0.3	50	25
			1.5	875	0.3	37	25
	Pressure Hydrated Lime		3.0	1100	0.6	62	20
			2.0	1100	0.6	56	28
	Dolomite	33	2.5	1100	0.6	44	18
		33	3.0	1100	0.6	51	17
Eastern U.S. Bituminous	Pt. Anne Limestone	3.9	3.6	1300	>0.7	37	10
			3.6	1100	0.6	59	16
			3.6	875	0.3	63	18
			3.0	875	0.3	54,56,60	19
			2.5	875	0.3	53	21
			2.4	875	0.3	46	19
			2.0	875	0.3	47,39	24,20
			1.8	875	0.3	34	19
W. Can. - U.S. Blend	Beachville Limestone	8.6	3.0	1100	0.6	46	16
			3.0	1300	>0.7	30	10
			3.0	875	0.3	42	14
			1.5	1100	0.6	22	15
			2.0	1100	0.6	28	14
			2.5	1100	0.6	39	16
			3.5	1100	0.6	47	14
			4.0	1100	0.6	50	13

Sulphur capture from the US coal by Beachville limestone and hydrated lime as a function of operating variables is plotted in Figure 6. The corresponding response surface diagrams are shown in Figure 7. The data indicate that sulphur capture is a strong function of injection temperature, Ca/S ratio and residence time in the sulphation window. Increased absorption is favored by increased temperatures, increased Ca/S ratios and increased residence times.

The performance of the four sorbents under optimized operating conditions for the Lakeview quenching rate is compared in Figure 8. The sorbents include hydrated lime, dolomite, Pt. Anne limestone and Beachville limestone.

As expected the highest sulphur capture and sorbent utilization was achieved by hydrated lime. Pt. Anne limestone performed much better than the Beachville limestone probably because of its high porosity. Highly porous dolomite was also an efficient sorbent. At an injection temperature of about 875 - 1100°C, Ca/S ratio of 2.5 to 3 and about 0.3 - 0.6s residence time, up to 43% of SO_2 can be removed from the flue gases by injecting limestone, 56% by Pt. Anne limestone, 63% by hydrated lime and 51% by dolomite. The corresponding sorbent utilizations (% SO_2 capture/Ca/S) are: 14%, 19%, 25% and 17%.

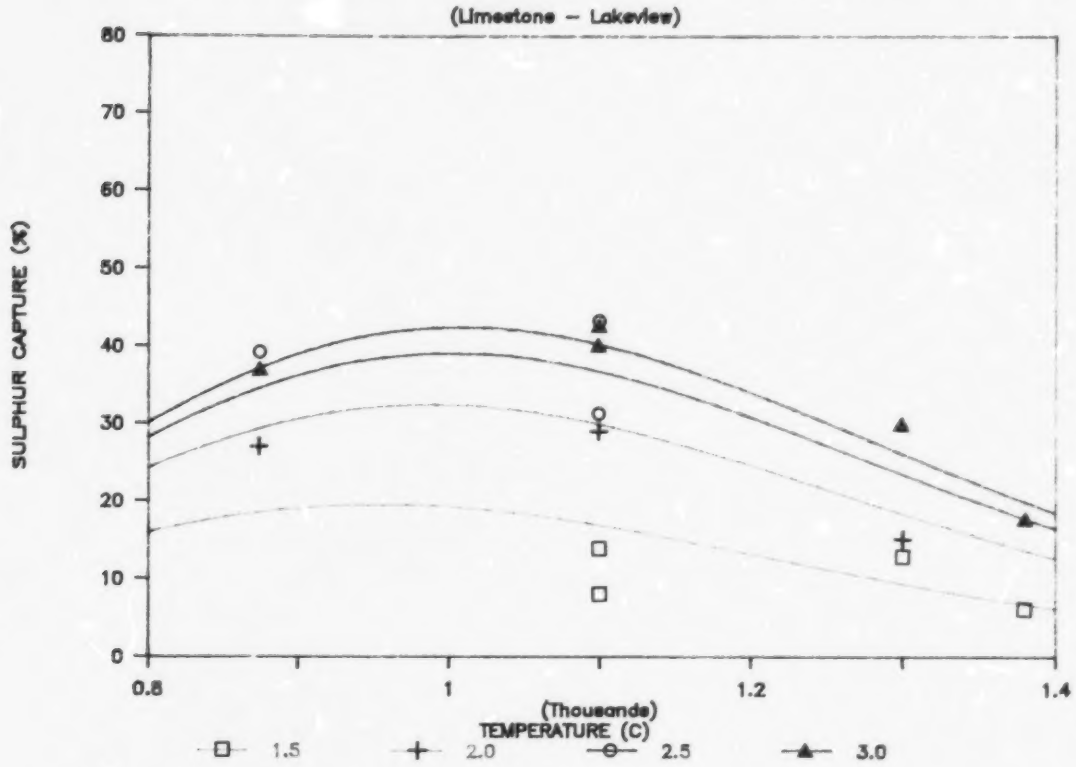
SO_2 capture vs porosity of chemically similar sorbents (carbonates) shown in Figure 9 indicate, that porosity is indeed very important in determining sorbent reactivity: the higher the porosity the higher the sulphur capture. Hydrated lime being chemically different has higher reactivity than carbonates for the same level of porosity.

Increasing residence time in the furnace from 600 to 900 ms, achieved by reducing furnace quenching rates from 500°C/s to 280°C/s, improved sulphur capture and sorbent utilization for Beachville limestone injection from 43% to 52%. Increased residence time had less effect for hydrated lime: sulphur capture increased from 65 to 70% (See Table 5).

The comparison of the full scale and pilot scale results is presented in Figure 10 where sulphur capture under similar operating conditions from the full scale experiment is plotted versus pilot scale results. The closer these points are to the diagonal line the better the agreement between the two sets of data and the more reliable predicative capabilities the model has. Considering the difficulty of measuring temperatures at full scale boilers, the agreement between the two sets of data seems to be reasonably good. One exception is test number 8a (see Figure 10) which is probably due to inconsistent sorbent feeding.

5.2 Comparison of Coals

A few runs were also carried out to remove sulphur from flue gases by injecting Beachville limestone into the furnace when burning a 1.4% S 50:50 blend of a W. Canadian - U.S. Coal (see Table 4). SO_2 capture and sorbent utilization as a function of injection temperature and Ca/S ratio are compared in Figure 11 for the coal blend and US coal under identical operating conditions.



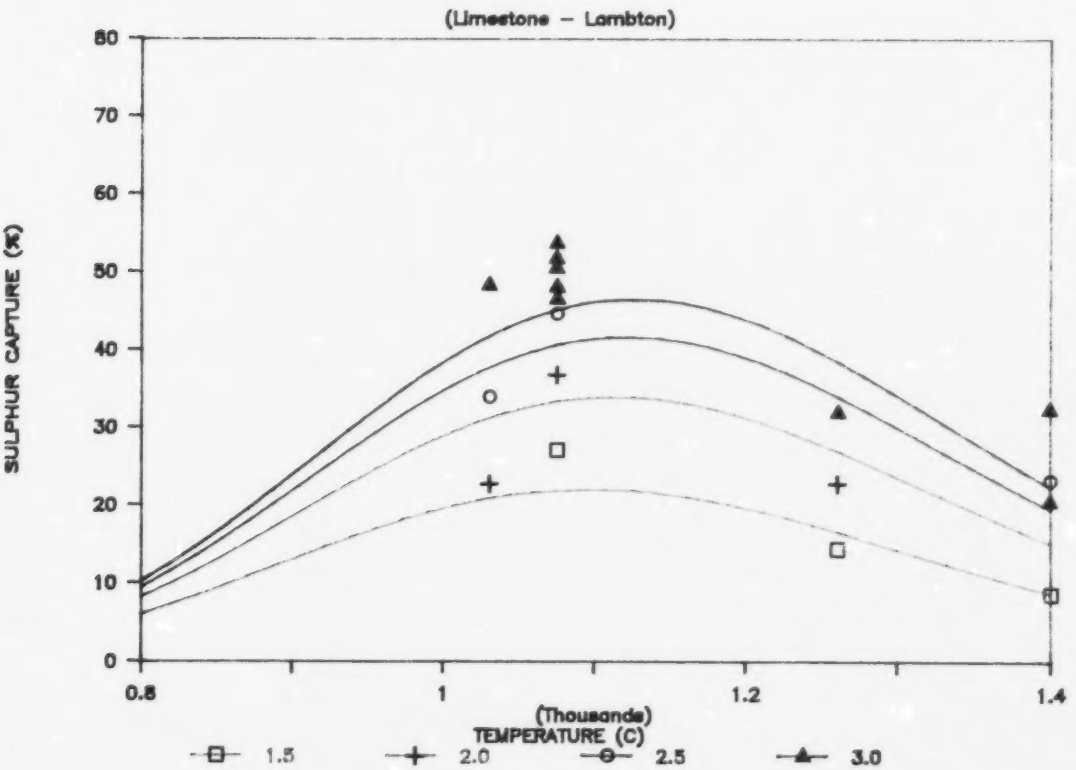
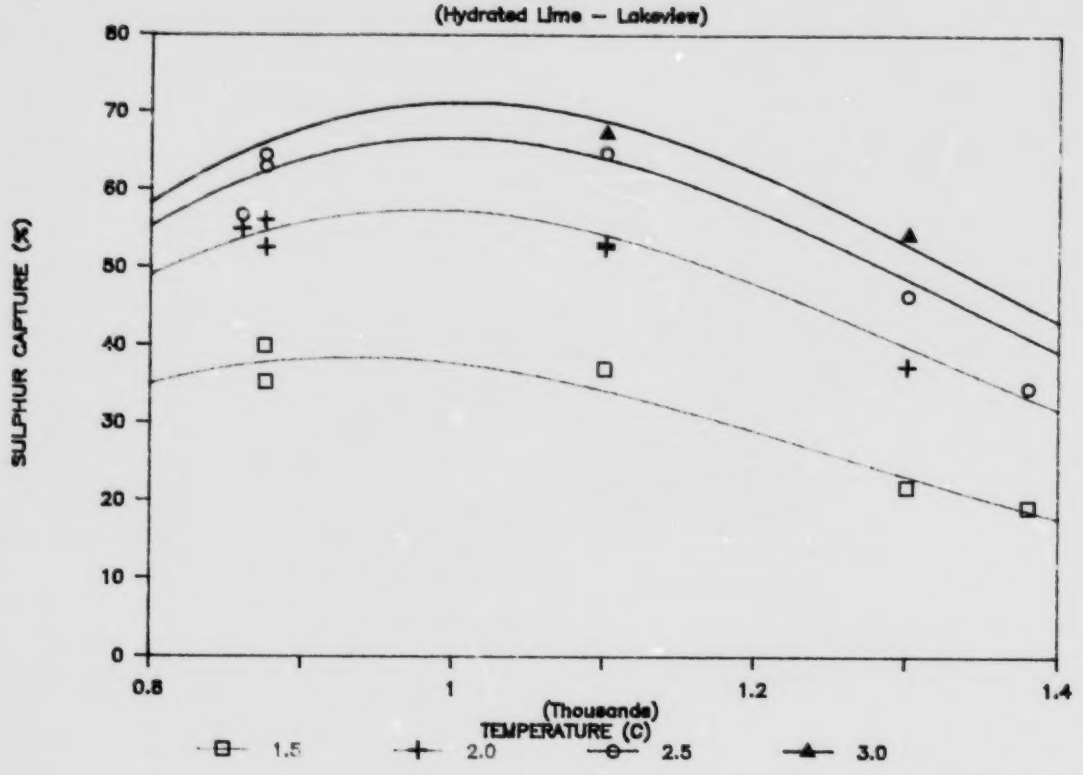


FIGURE 6 SULPHUR CAPTURE



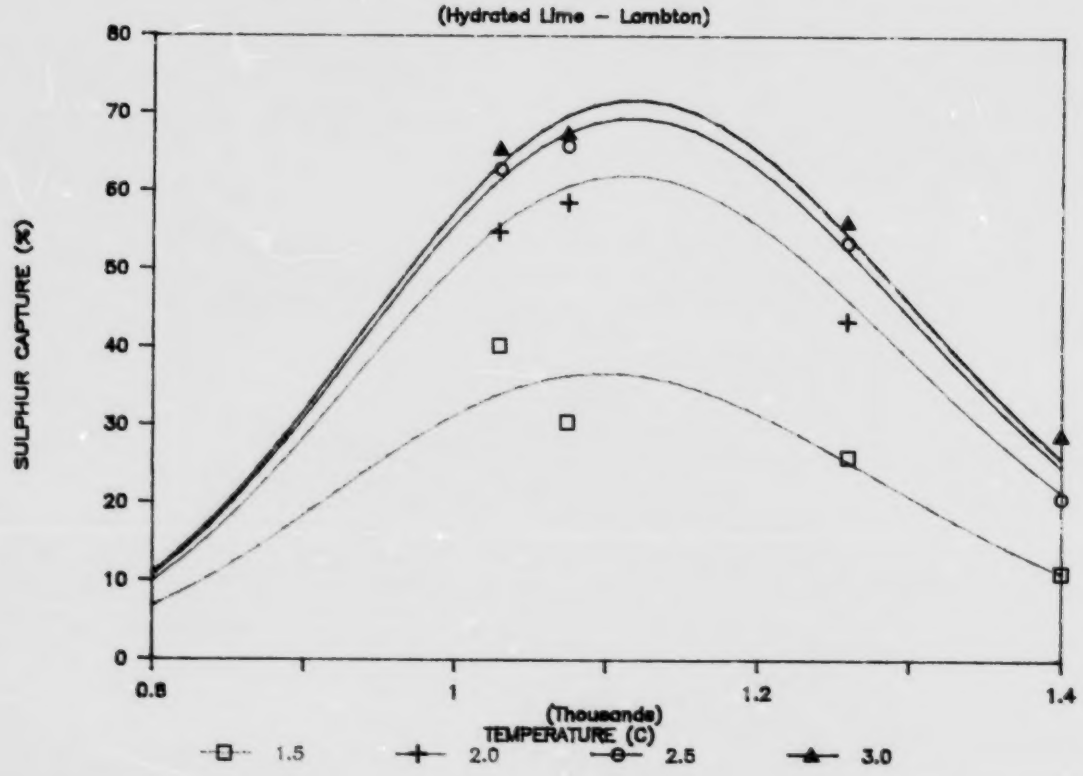
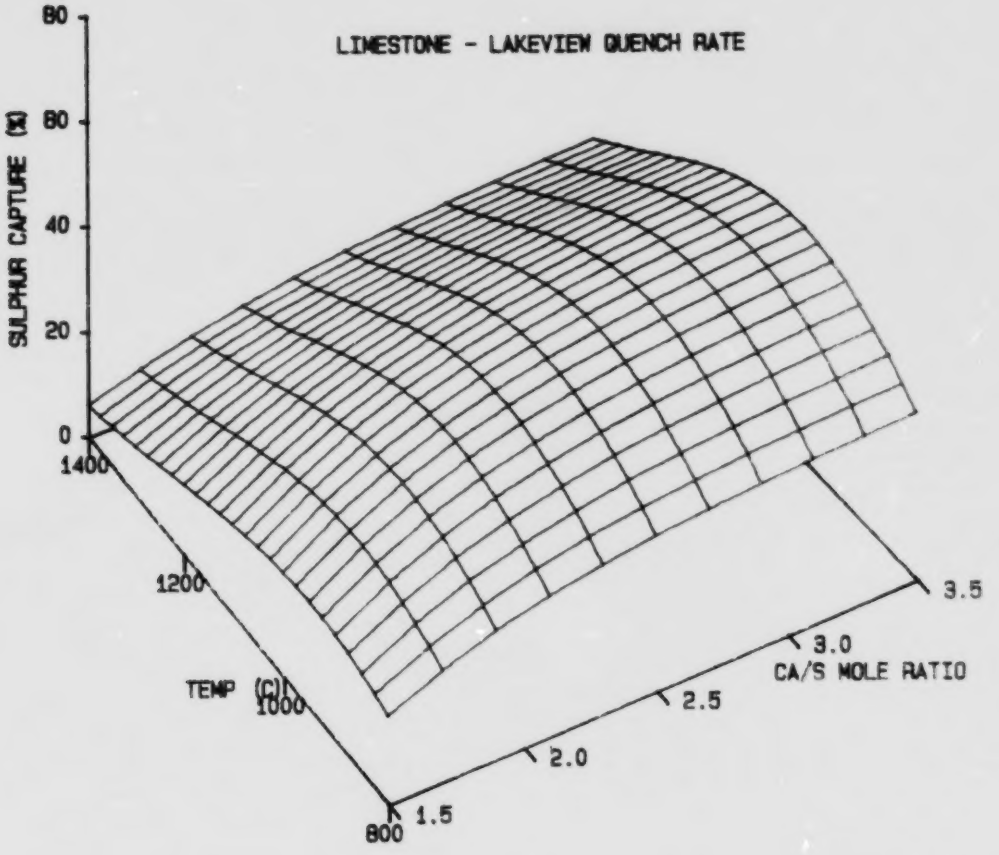


FIGURE 6 (cont'd) SULPHUR CAPTURE



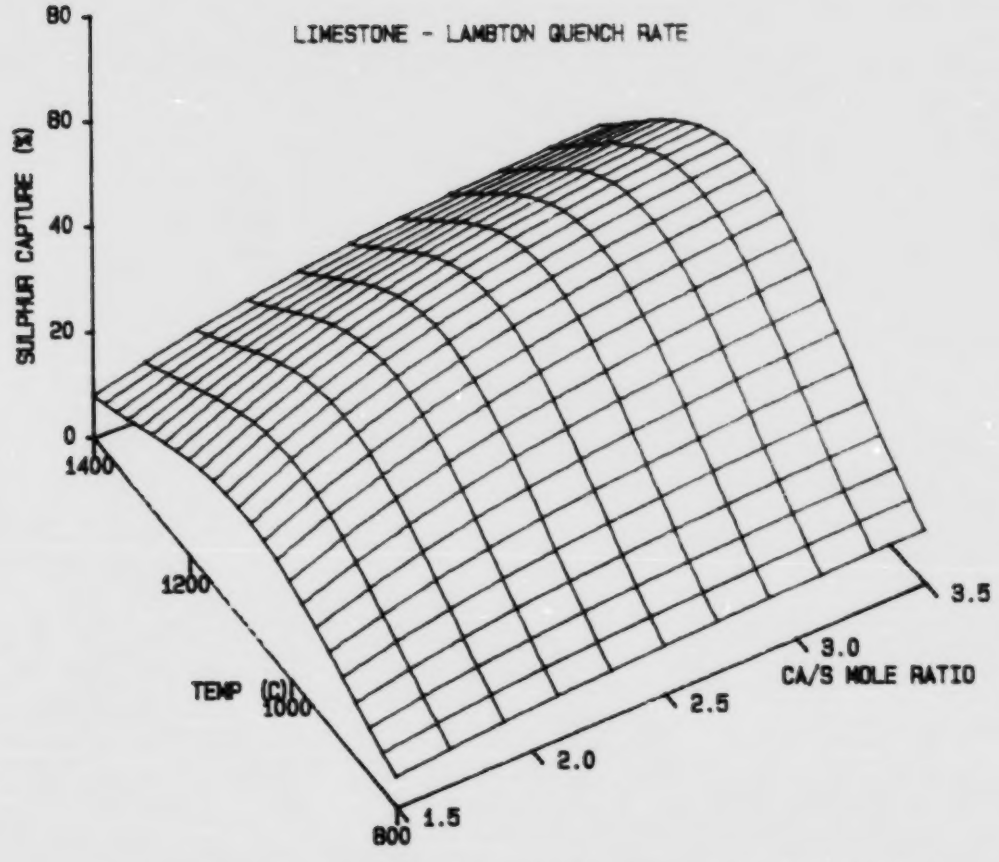
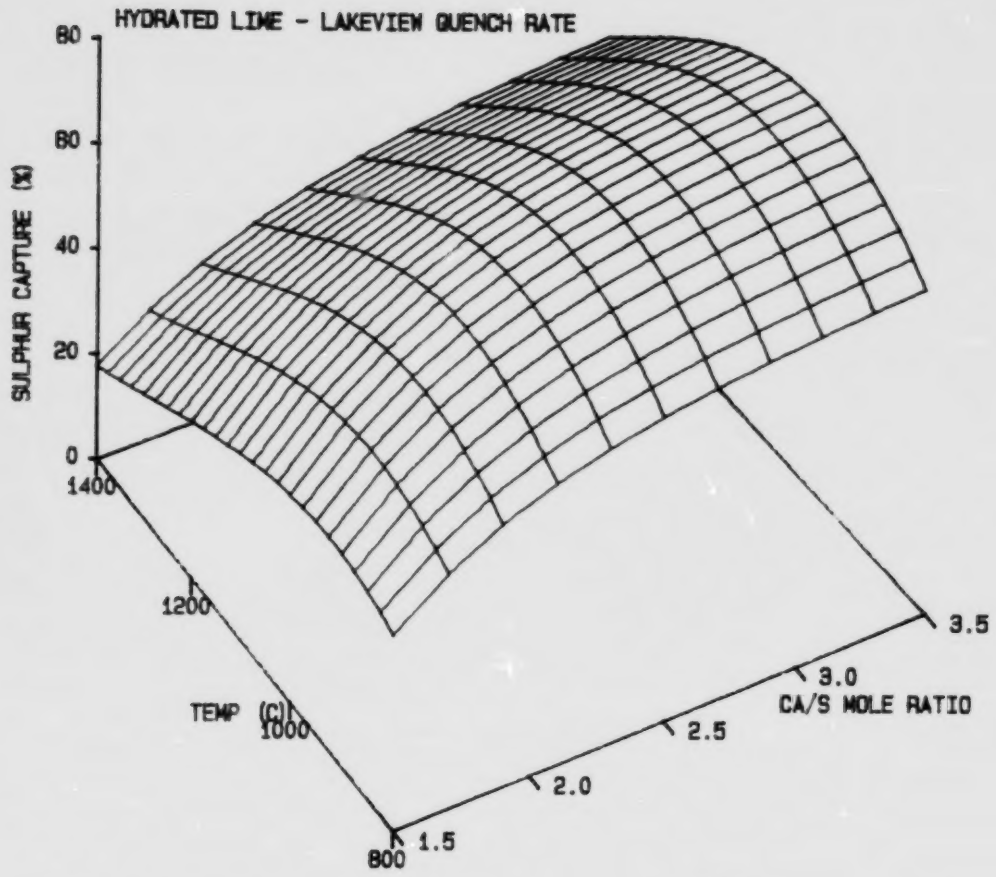


FIGURE 7 SULPHUR CAPTURE RESPONSE SURFACE



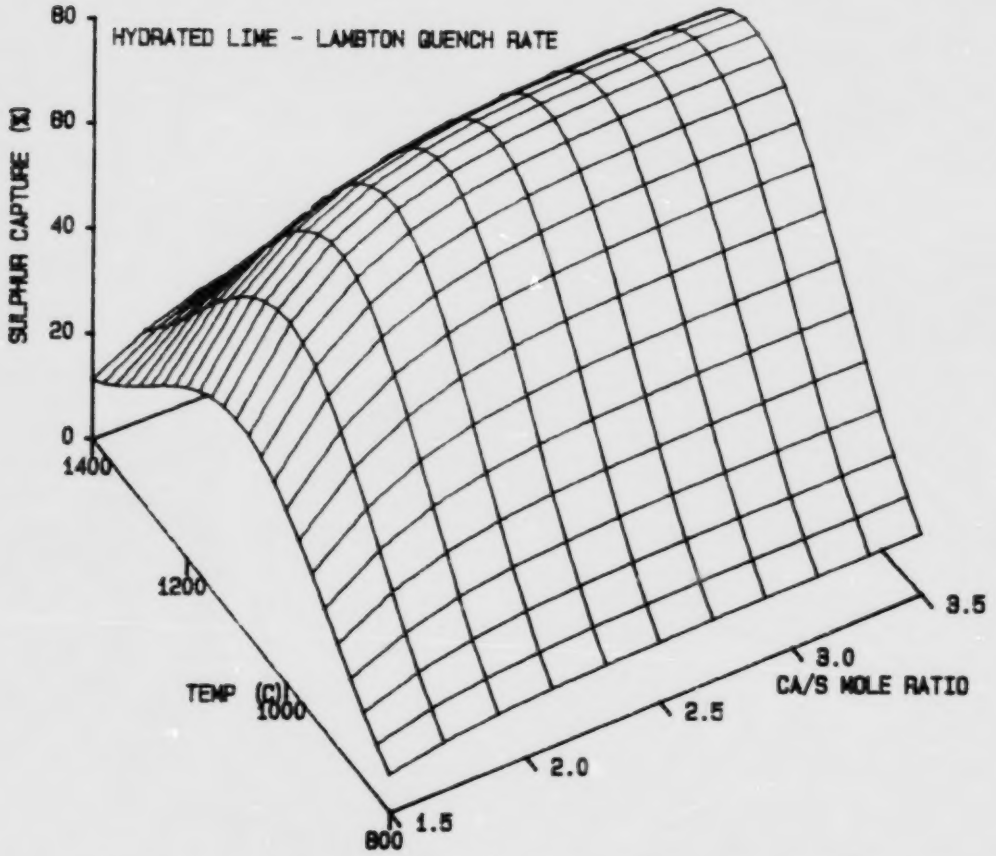


FIGURE 7 (cont'd) SULPHUR CAPTURE RESPONSE SURFACE

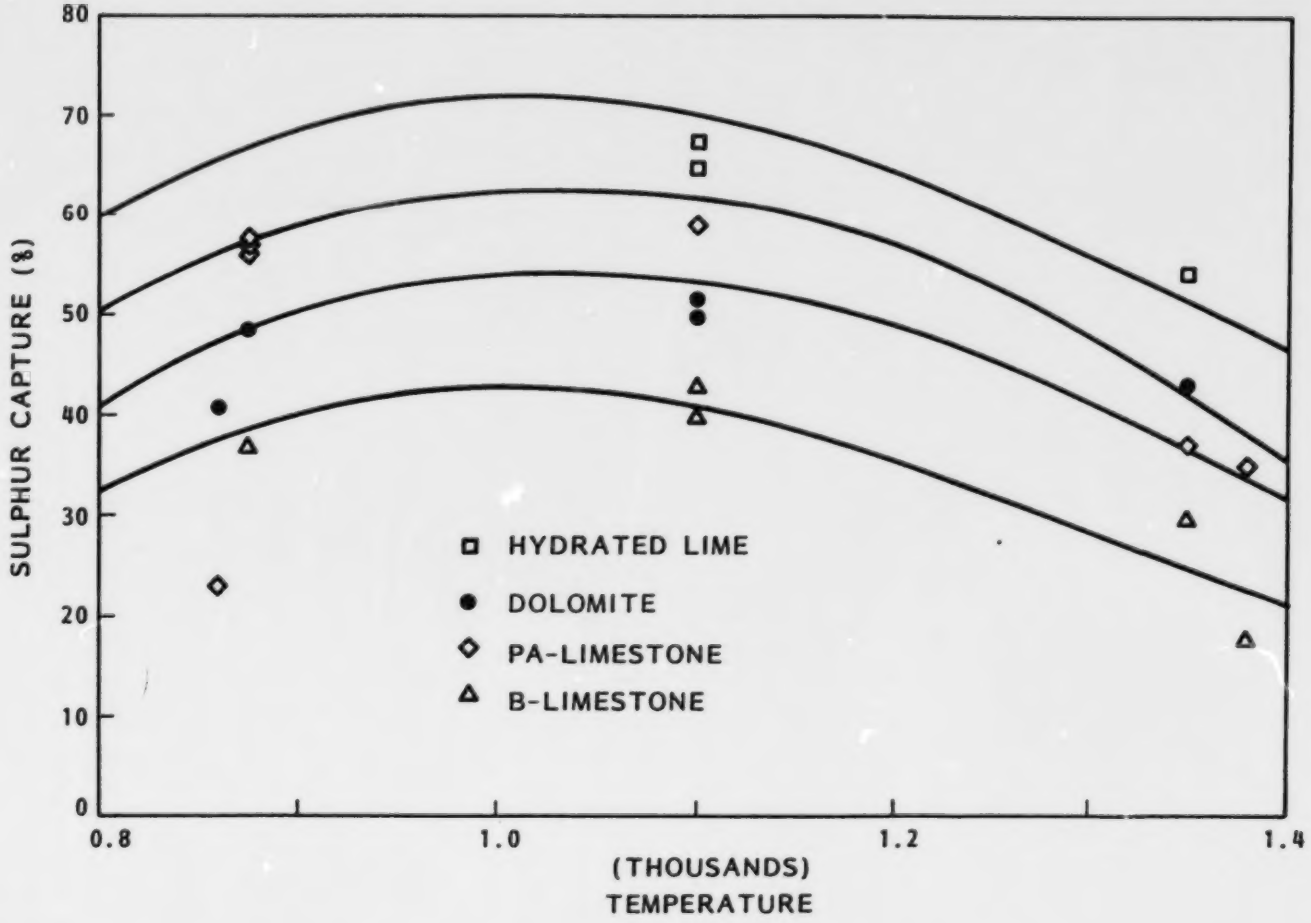


FIGURE 8

COMPARISON OF SORBENT PERFORMANCE
Lakeview TGS Quenching Rate (500°C/s)
Ca/S Ratio = 2.5 - 3.0

88-63
176632-pi

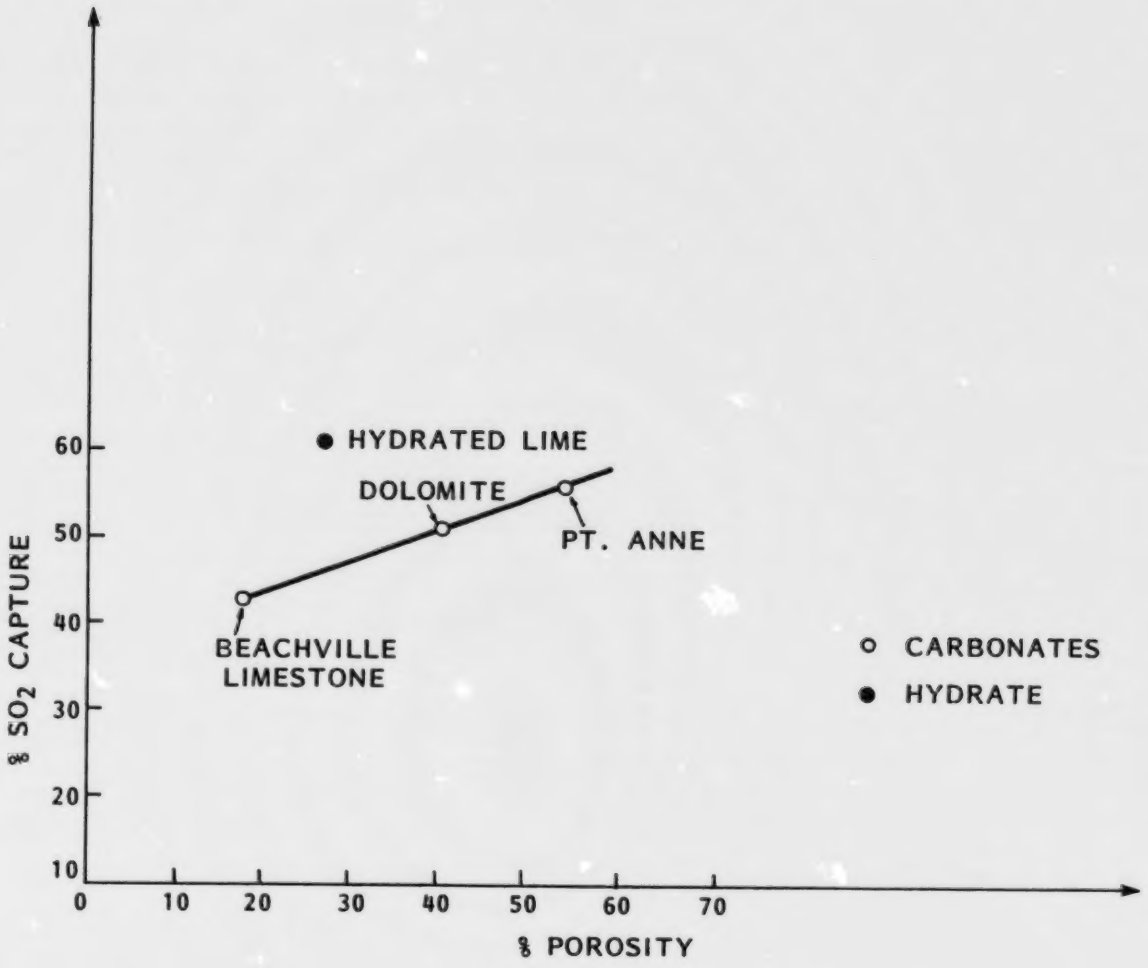


FIGURE 27

CORRELATION BETWEEN SO_2 CAPTURE AND POROSITY

Lakeview Quenching Rate: 500°C/s
Injection Temperature = 1100°C
Ca/S Ratio = 2.5 - 3.0

TABLE 5 - OPTIMIZED PROCESS PERFORMANCE
Injection Temp = 1100°C, Ca/S ratio = 2.5 - 3.0

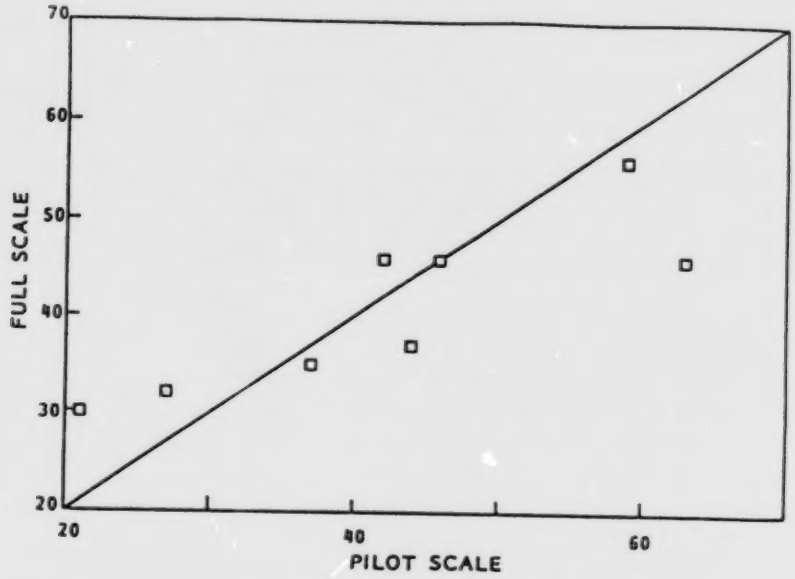
Coal		Residence Time	Hydrated Lime	Dolomite	Limestone
US Bituminous, S = 1.7%	% SO_2 Capture	600 ms	65	51	43
		900 ms	70		52
	% Sorbent Utilization	600 ms	26	17	14
		900 ms	28		17
W. Canadian-U.S. Blend, S = 1.4%	Capture	600 ms			46
	% Sorbent Utilization	600 ms			15

As the results indicate sulphur capture and sorbent utilization follows similar patterns for both the US coal and Western Canadian-US coal blend. At optimum injection temperature of 1100°C and Ca/S ratio of 2.5 - 3.0 sulphur capture from flue gases of the coal blend are slightly higher, being about 46% as compared to 43% for the US coal. The corresponding optimum sorbent utilizations are 14 and 15%.

Soft deposits, which form at low temperatures and are generally characteristic of deposits found on air heaters and economizers, were observed on the furnace walls and heat exchanger surfaces. These deposits could be easily blown away by compressed air suggesting that conventional soot blowing equipment may suffice for full scale boiler sorbent injection. Deposition of particles on the surfaces of the heat exchangers did impair their heat transfer rates but no severe adverse effects due to slagging were observed during the test burns with either the US coal or the blend.

5.3 Humidification

Low temperature humidification of the sorbent injection waste to achieve additional sulphur capture and improve ESP performance was also evaluated on the pilot scale. Since calcium utilization by in-furnace sorbent injection is low, the fly ash contains large amounts of unreacted CaO (calcine). Water injection into the humidifier activates the CaO so that additional sulphur capture takes place. The additional sulphur capture increases sorbent utilization and thus can significantly improve process economics. Other benefits of the humidification process include reducing particulate resistivity and cooling of the flue gas. Cooling results in lower gas volumes



TEST NO	LOAD MW	SORBENT	INJECTION ELEV (ft)	INJECTION TEMP; T_I (°C)	RESIDENCE TIME, S T_I - 850	SO_2 CAPTURE %	SORBENT UTILIZATION %
1a	300	$CaCO_3$	339	1380 (est)	>0.7	30	12
1b	0.2 (Pilot)	$CaCO_3$		1380	>0.7	21	8
2a	220	$CaCO_3$	339	1220	1.1	35	14
2b	0.2 (Pilot)	$CaCO_3$		1220	1.1	37	15
3a	300	$Ca(OH)_2$	339	1380 (est)	>0.7	46	18
3b	0.2 (Pilot)	$Ca(OH)_2$		1380	>0.7	42	17
4a	220	$Ca(OH)_2$	339	1220	1.2	56	22
4b	0.2 (Pilot)	$Ca(OH)_2$		1220	1.2	59	24
5a	300	$CaCO_3$	357	1320	>0.7	32	13
5b	0.2 (Pilot)	$CaCO_3$		1320	>0.7	27	11
6a	220	$CaCO_3$	357	1180	1.1	37	15
6b	0.2 (Pilot)	$CaCO_3$		1180	1.1	44	18
7a	300	$Ca(OH)_2$	357	1320	>0.7	46	18
7b	0.2 (Pilot)	$Ca(OH)_2$		1320	>0.7	46	18
8a	220	$Ca(OH)_2$	357	1180	1.1	46	18
8b	0.2 (Pilot)	$Ca(OH)_2$		1180	1.1	63	25

Ca/S Mole Ratio: 2.5
Limestone Particle Size: 81% - 325 Mesh (MMD = 8.6 μm)
Hydrated Lime Particle Size: 84% - 325 Mesh (MMD = 8.2 μm)

177045-RD
Bart 2 Disk

FIGURE 10
COMPARISON OF PILOT AND FULL SCALE DATA

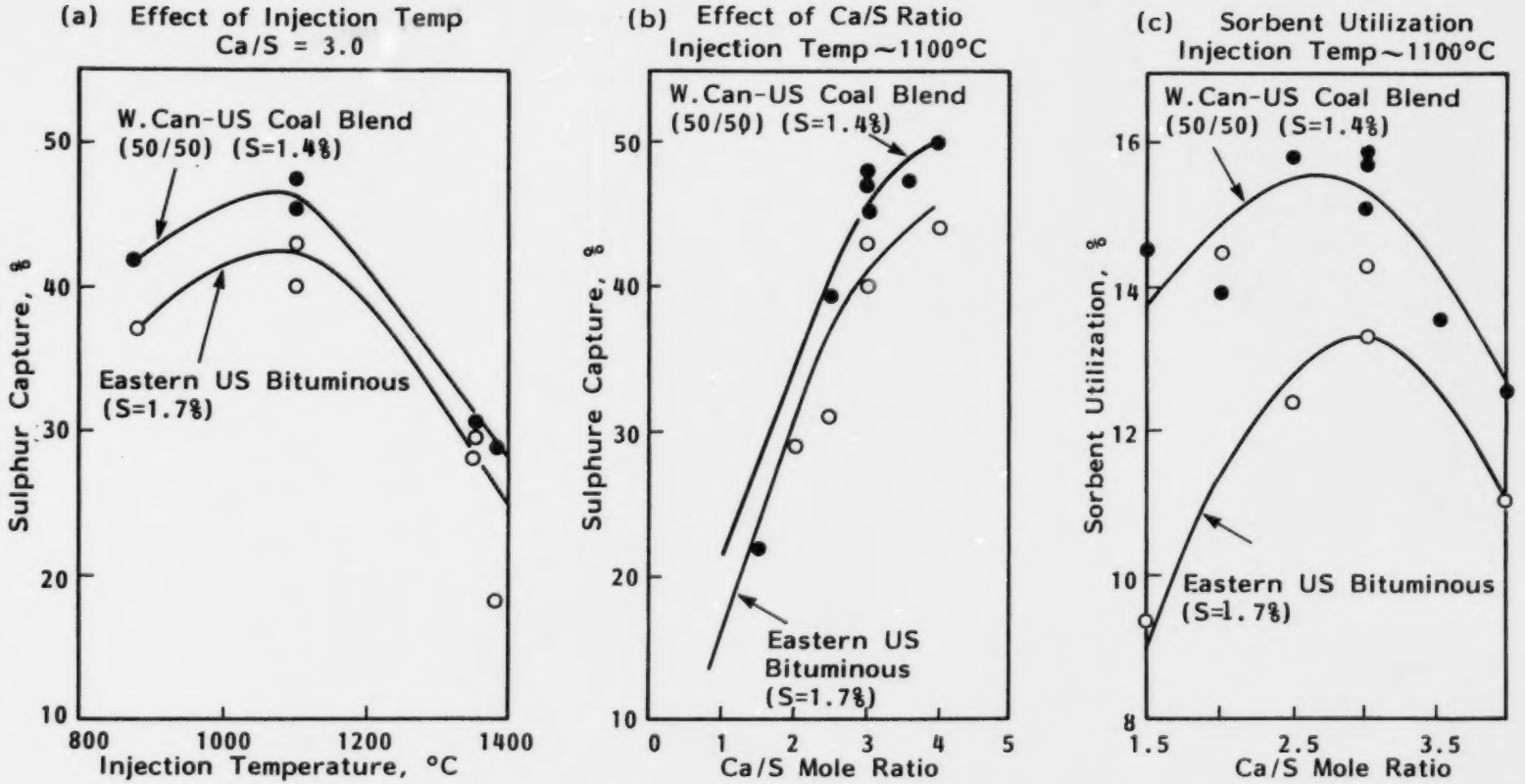


FIGURE 11

COMPARISON BETWEEN WESTERN CANADIAN-US COAL BLEND
AND EASTERN US BITUMINOUS COAL

Lakeview TGS Quenching Rate, 500° C/s
Beachville Limestone, 8.6 μm MMD

which means a higher effective SCA for the precipitator. Both reduced resistivity and lower gas volume are instrumental in improving ESP performance.

The importance of flue gas humidity in promoting low temperature reaction between CaO and SO_2 had been first noticed in spray drier applications, where fabric filters treating flue gas, humidified to within 20°F approach to adiabatic saturation were observed to remove up to 100% of the remaining SO_2. The actual mechanism of sulphur capture is not fully understood but it was noted by researchers studying reactions of dry lime particles with SO_2/20/, that the lime particles containing a small amount of moisture on their surface (equivalent to at least one molecular layer), give rise to significant SO_2 capture. Moisture adsorption isotherms indicate that the amount of water equivalent to one molecular layer is adsorbed on lime particles at about 20% relative humidity. This corresponds to approximately 40 to 45°F approach to adiabatic saturation.

The objective of the pilot scale studies on humidification is to evaluate the in-furnace injection-humidification process for large scale retrofit application, under conditions simulating Ontario Hydro's boilers. The various aspects of the study included:

- humidification system design, nozzle selection and optimization;
- evaluating and optimizing sulphur capture in the humidifier by various in-furnace injected sorbents as a function of operating variables such as nozzle type, droplet particle size, residence time and relative humidity;
- evaluating the effect of humidification on ash resistivity and ESP performance.

5.3.1 Nozzle Selection

The four spray nozzles selected and compared include: Turbotak Caldyn, 2 mm nozzle; Sonic Development ST-47 and 052 MBX-1 nozzles; and a Spraying System 1/4 J nozzle. During the tests, a Beachville limestone, having a mass median diameter of 8.6 μm at a Ca/S ratio of 3 was injected at 1100°C into the furnace. SO_2 removal was 40 to 43%. Water was injected into the humidifier at a steady rate of 120 ml/min at a 75 to 80 psig air pressure. The relative humidity level at this rate is 50 to 60%. SO_2 capture in the humidifier by the various nozzles was monitored. The results are shown in Table 6.

The data indicate that the Turbotak Caldyn 2 mm nozzle has the most favourable spray characteristics. It produces the finest droplet size: 5-10μm, narrowest spray angle :12-15°, shortest droplet drying time :0.9 sec and did not exhibit any caking tendency. As expected it outperformed all the other nozzles tested and gave the highest, 18% SO_2 capture in the humidification chamber, without any deposit build-up. Therefore this nozzle was selected for the humidification studies. The droplet size distribution for the two "best" nozzles is shown in Figure 12.

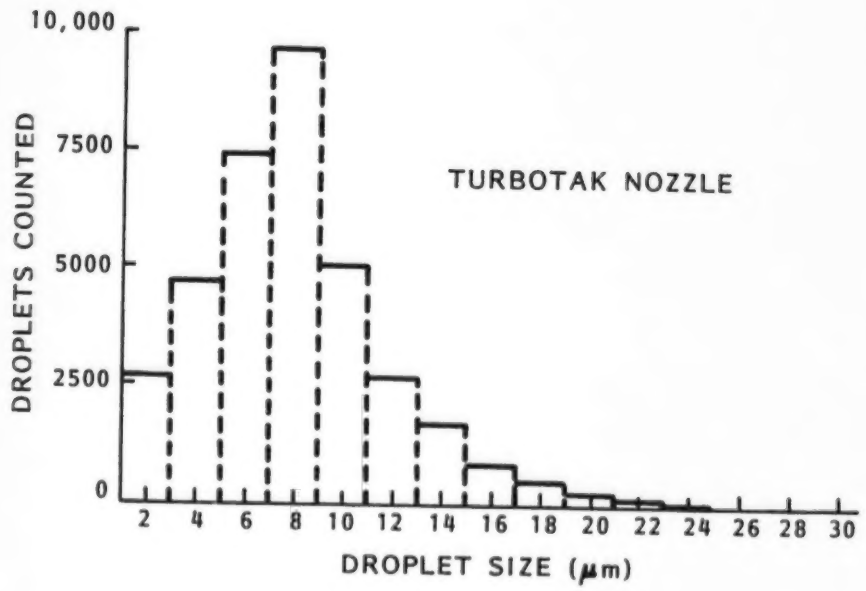
TABLE 6

NOZZLE SELECTION

120 cc/min water
50 - 60% relative humidity
75 - 80 psig air pressure

NOZZLE TYPE (TWO FLUID)	SPRAY ANGLE, °	MEAN DROPLET SIZE, μm	DROPLET DRYING TIME, S	OBSERVATION	INCREMENTAL SO_2 REMOVAL, %
Tubotak Caldyn 2 mm	~12 - 15	5 - 10	~0.9	No Caking	18
Sonic Development ST-47	~15 - 20	20 - 30	~1.3	Caking	12
Sonic Development 052 MBX-1	~15 - 20	20 - 30	-	Severe Caking	-
Spraying System 1/4 J	~18	10 - 25	~1.3	No Caking	11

Front End Conditions: Infurnace Beachville Limestone Injection
Inj Temp ~1100°C
Ca/S Mole Ratio: 3.0
Limestone Particle Size - 8.6 μm MMD
SO_2 Removal ~40 - 43%



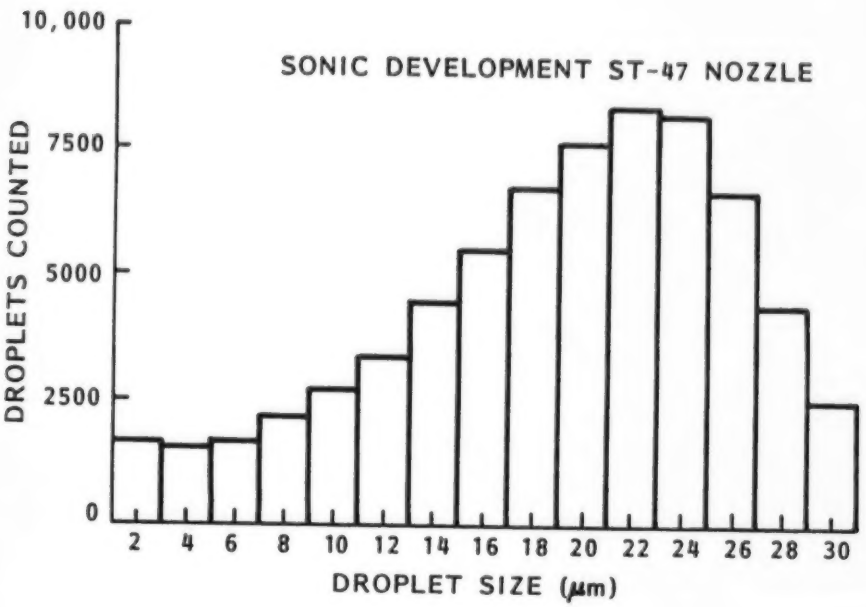


FIGURE 12
DROPLET SIZE DISTRIBUTION
Inlet Air Pressure = 80 psig
Water Flow Rate: 120 ml/min

5.3.2 Optimizing Conditions in the Humidifier

The effect of operating conditions in the humidifier on SO_2 capture was investigated using a waste produced by the in-furnace injection of limestone at about 1100°C, and at a Ca/S ratio of 3:1, when burning a 1.7% S US coal. Under these conditions the in-furnace sulphur capture was 43%. This waste was then humidified in the chamber and the incremental SO_2 capture (Inc. SO_2 cap = $(SO_2$ in $- SO_2$ out$)/SO_2$ total in flue gas) as a function of operating variables was measured. The variables studied include: water droplet size, initial gas humidity level and residence time in the humidifier (this latter was varied by changing the location of the nozzle). The results - plotted in Figure 13 show that: SO_2 capture increases with decreasing droplet size and increasing initial gas humidity. It appears that SO_2 concentration drops very rapidly within about 0.5 - 1.0 sec and this drop in SO_2 level coincides with the rapid drop in gas humidity. Once the gas humidity is ~ 35%, there is no more SO_2 capture.

As a result of this study the optimum operating conditions in the humidifier at inlet gas temperatures ranging from 147 - 153°C and using a Turbotak Caldyn 2 mm nozzle, were established as follows:

Water flow rate to the nozzle	: 120 ml/min
Atomizing air pressure	: 80 psig
MMD of water droplet	: 5-10 μm
Relative humidity at injection site	: ~60%
Outlet gas temp	: 60 - 65°C

5.3.3 SO_2 Capture by Sorbent Injection - Humidification

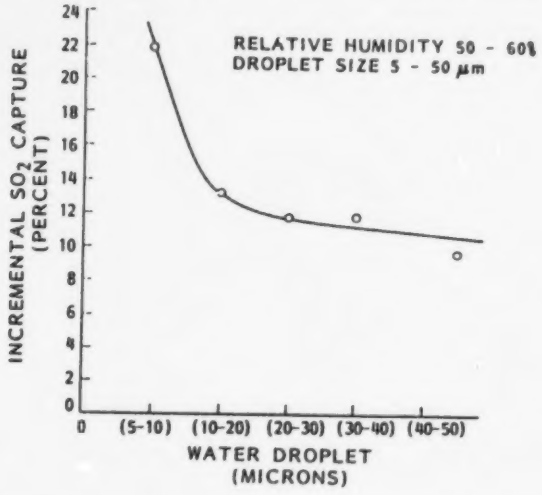
The integrated process was studied by injecting the various sorbents into the furnace at Ca/S ratios ranging between 1.5 to 3 and temperatures between 875 and 1200°C (1607-2192°F). The ash was then humidified in the humidifier using a Turbotak Caldyn 2 mm nozzle, at optimized operating conditions.

The various wastes humidified include: sorbent injection wastes produced by the injection of Beachville limestone into the furnace when burning a 1.7% S US and a 1.4% S US - W. Canadian blend; and wastes produced by injecting hydrated lime, and dolomite at various temperatures and Ca/S ratios while burning the US coal. The results are summarized in Table 7.

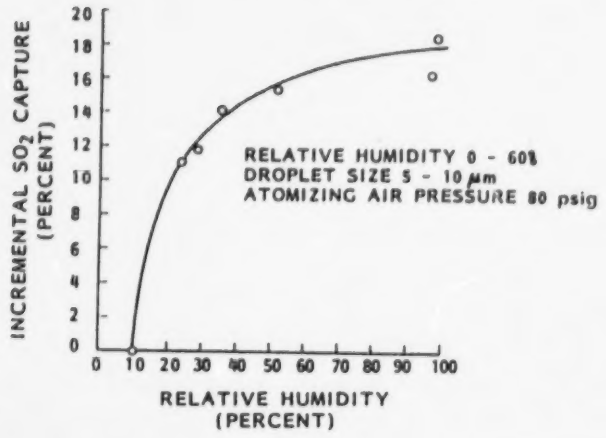
The results indicate that effectiveness of waste humidification depends not only on the operating conditions in the humidifier but it is also a function of waste characteristics. It appears that the lower the SO_2 removal in the furnace (at low temperature injection or at low Ca/S ratios) the higher it is in the humidifier.

Hydrated lime performs well during in-furnace sorbent injection (at favourable injection conditions, SO_2 capture is ranging between 61 to 65%) but SO_2 capture in the humidifier is very low, only 1.6 to 6.0. At low temperature and low Ca/S ratios, sulphur capture in the furnace drops but increases in the humidifier. The same trend is observed with limestone. A plot of SO_2 capture

(a) Effect of Water Droplet Size


RELATIVE HUMIDITY 50 - 60%
DROPLET SIZE 5 - 50 μm
INCREMENTAL SO_2 CAPTURE (PERCENT)
0 2 4 6 8 10 12 14 16 18 20 22 24
0 (5-10) (10-20) (20-30) (30-40) (40-50)
WATER DROPLET (MICRONS)

(b) Effect of Gas Humidity


RELATIVE HUMIDITY 0 - 60%
DROPLET SIZE 5 - 10 μm
ATOMIZING AIR PRESSURE 80 psig
INCREMENTAL SO_2 CAPTURE (PERCENT)
0 2 4 6 8 10 12 14 16 18 20
0 10 20 30 40 50 60 70 80 90 100
RELATIVE HUMIDITY (PERCENT)

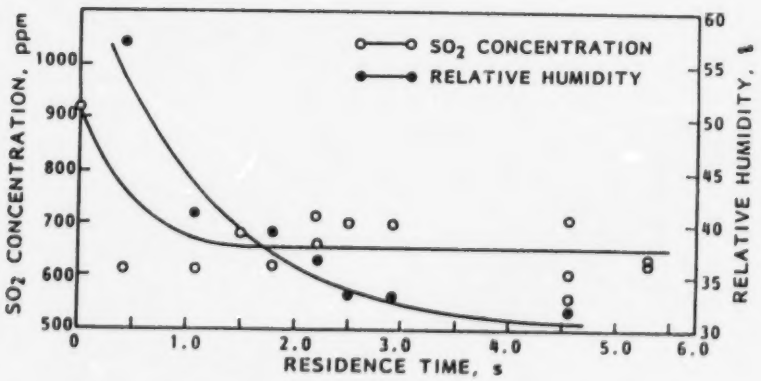

SO_2 CONCENTRATION
RELATIVE HUMIDITY
SO_2 CONCENTRATION, ppm
500 600 700 800 900 1000
RELATIVE HUMIDITY, %
30 35 40 45 50 55 60
0 1.0 2.0 3.0 4.0 5.0 6.0
RESIDENCE TIME, s

FIGURE 13

HUMIDIFICATION - EFFECTS OF OPERATING VARIABLES
Turbotak Caldyn Nozzle, 2 mm, Front End SO_2 Removal
40 - 43%, Water Flow Rate ~120 cc/min

TABLE 7

SO_2 REMOVAL BY IN-FURNACE INJECTION - HUMIDIFICATION

		IN-FURNACE INJECTION							HUMIDIFICATION			TOTAL	
COAL	PPM SO_2 IN FLUE GAS	SORBENT TYPE	MMD μm	Ca/S RATIO	INJECTION TEMP, °C	RESIDENCE TIME, S	% SO_2 CAPTURE	% SORBENT UTILIZATION	SO_2 IN HUMIDIFIER (ppm)	SO_2 OUT HUMIDIFIER (ppm)	% SO_2 CAPTURE	% SO_2 CAPTURE	% UTILIZATION
U.S. Bituminous S=1.7%	1710	Beachville Limestone	8.6	3.0	1200	0.7	23	8	1315	839	28	51	17
	1475			3.0	1100	0.6	43	14	841	590	18	61	20
	1770			3.0	875	0.3	39	13	1080	796	16	55	18
	1480	Beachville Hydrated Lime	8.2	2.5	1100	0.6	63	25	548	522	1.6	65	26
	1633			3.0	875	0.3	65	22	577	545	2.0	67	22
	1632			2.5	875	0.3	61	24	627	533	5.7	67	27
	1632			2.0	875	0.3	50	25	816	720	6.0	56	28
	1632			1.5	875	0.3	37	25	1031	800	14.1	51	34
		Pressure Hydrated Lime		3.0	1100	0.6	62	20					
				2.0	1100	0.6	56	28					
	2100	Dolomite	33	2.5	1100	0.6	44	18	1176	1040	7	51	20
			33	3.0	1100	0.6	51	17					
W. Canadian U.S. Blend S = 1.4%	1632	Beachville Limestone	8.6	3.0	1100	0.6	46	15	881	707	11	57	20

in the furnace vs SO_2 in the humidifier for all the sorbents studied illustrates this point (Figure 14). The reason for this behavior is not exactly clear but it appears that high sulphur capture in the furnace results in more surface coating of CaO by $CaSO_4$, making it inaccessible for interaction with water in the humidifier. Work continues to elucidate the mechanism of the humidification step, to understand the reason for the different behavior of the various sorbents and the effect of furnace operating conditions.

The highest sulphur capture by in-furnace injection-humidification with US coal and limestone is 61% (43% in the furnace, 18% in the humidifier), and with W. Canadian - U.S. coal blend is 57% (46% in the furnace, 11% in the humidifier). Dolomite captures 44% in the furnace but only 7% in the humidifier. With hydrated lime maximum capture in the two step process is 67%, 61% in the furnace, but only 5.6% in the humidifier or 65% in the furnace and 2% in the humidifier, depending on the condition during in-furnace injection.

It appears that limestone is more desirable for the two step process than more reactive sorbents such as dolomite or hydrated lime.

5.4 Impact on Ash Characteristics, Collectability and Deposition

During furnace sorbent injection (FSI), fly ash is intimately mixed with reaction products (mainly $CaSO_4$) and unreacted sorbent (mainly CaO). With such waste some unanswered questions include: its impact on fly ash characteristics, precipitability, and deposition in the radiant section (slagging) and convective passes (fouling) of a boiler. Chemical composition, particle size distribution and carbon-content of the waste are also important aspects for design considerations for waste management systems. The effect on the back end of FSI was therefore studied and whenever available compared to full scale data.

5.4.1 Ash Characteristics

Particle size distribution and chemical composition of a few isokinetically collected ash samples from the injection of various sorbents are compared in Table 8 to baseline ashes (ashes without sorbent injection). The particle size distribution of limestone injection ash and of the baseline ash from the CRF are plotted in Figure 15.

The limestone injection ash is finer than the baseline ash: 80% of the limestone injection ash is less than 25 μm as compared to about 55% for the baseline ash. This is likely to produce a great increase in the mass loading of very fine particles, in the 1-2 μm range, where ESP collection efficiency is low.

The calcium compounds distribution, loss on ignition, carbon content, ash resistivities, dust loadings before and after the ESP and precipitator

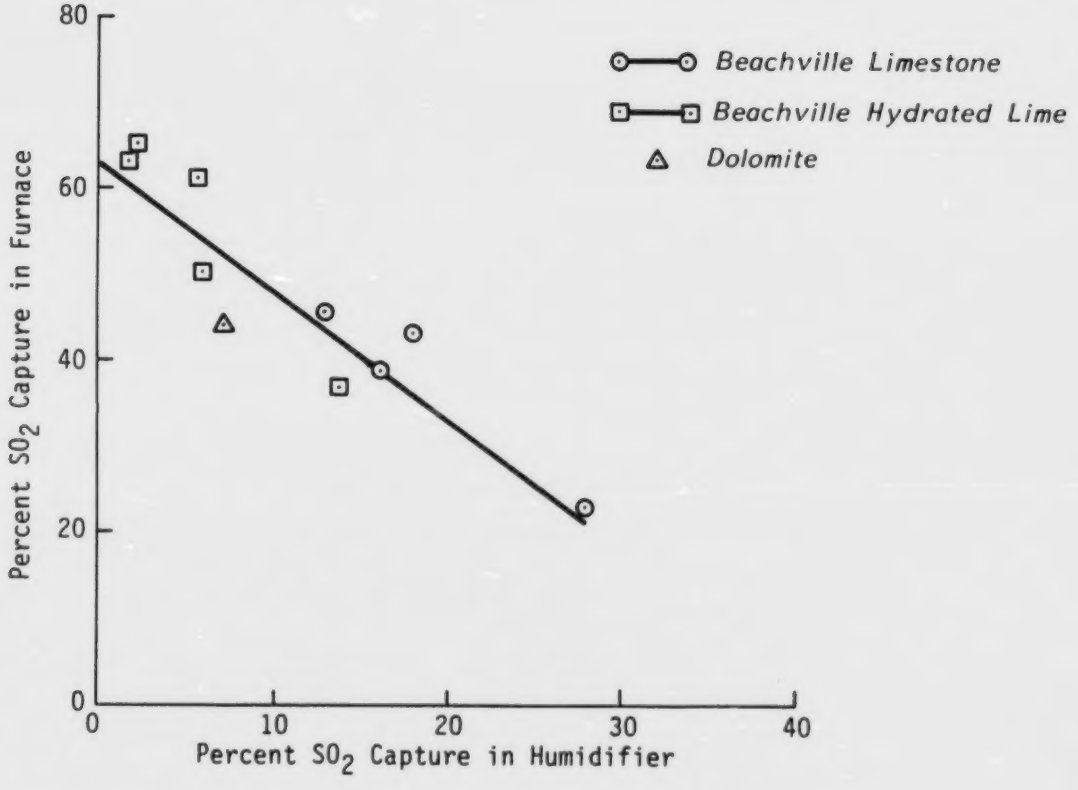


FIGURE 14

PERCENT SO_2 CAPTURE IN FURNACE VS IN THE HUMIDIFIER

TABLE 8

COMPARISON BETWEEN BASELINE AND LIMESTONE INJECTION ASHES

Particle Size Distribution

Sieve Opening μm	Cumulative % Undersize		
	Baseline Ash (CRF)	Limestone Injection Ashes CRF	*Lakeview TGS
7	10	13	7
17	54	74	41
37	60	92	76
44	92	94	
75	96	99	100
105	98	100	
250	100		

Chemical Composition, g/kg

	BASELINE ASH (CRF)	LIMESTONE INJECTION ASHES		HYDRATED LIME INJECTION ASHES		DOLOMITIC ASH CRF
		CRF	*LAKEVIEW TGS	CRF	*LAKEVIEW TGS	
Na_2O	6	3	2	2	3	7
K_2O	17	7	5	6	8	9
MgO	9	10	11	7	7	128
CaO	50	334	518	402	286	221
Fe_2O_3	77	38	54	57	97	84
Al_2O_3	215	110	66	112	109	121
SiO_2	451	225	159	196	248	213
TiO_2			3	6	5	7
SO_3	23	80	45	151	45	144
LOI	161	143	114	174	165	179

*Taken from Reference 21.

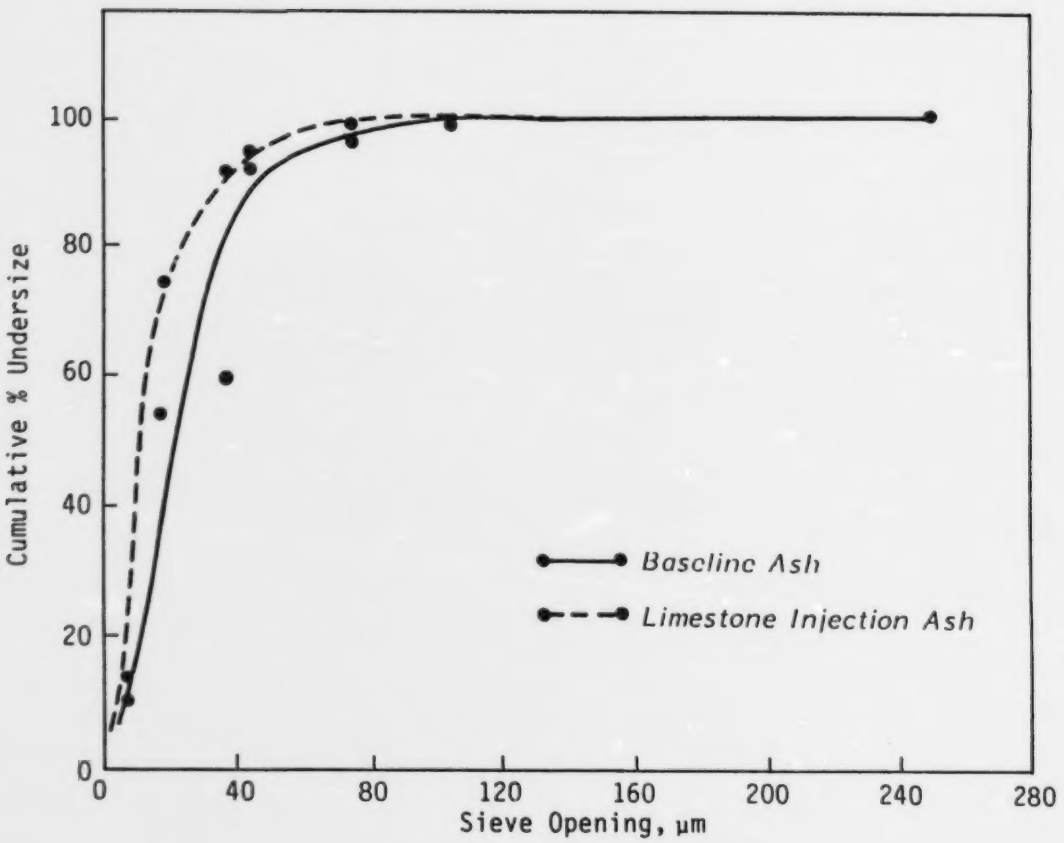


FIGURE 15

PARTICLE SIZE DISTRIBUTION OF BASELINE AND LIMESTONE INJECTION ASH AT THE CRF

performance are given in Table 9 for selected wastes, produced during the injection of various sorbents. Sorbent injection wastes contain high levels of calcium compounds ranging between 206-337 g/kg CaO and 77-256 g/kg $CaSO_4$ and small amounts of $CaCO_3$ (30-85 g/kg). This of course depends on the front end conditions such as Ca/S ratio and sulphur capture. It is interesting to note that the composite sample from the hydrated lime injection from Lakeview TGS contains lower than expected levels of $CaSO_4$ and CaO, based on the reported SO_2 capture. It is likely that the samples were not representative. The process produces about 18 kg waste/100 kg coal, approximately twice as much than the ash alone. High levels of calcium compounds in the waste and the large quantity produced are expected to pose very difficult problems in handling, disposal and collectability by the ESP.

Carbon levels of the sorbent injection waste range between 108-179 g/kg. On a sorbent free basis it amounts to about 100 to 200 g/kg, higher than without sorbent injection, indicating that the combustion process is slightly less efficient with sorbent injection. Preliminary calculations indicate that the heat losses due to the high carbon in ash typically are about 1.1% for sorbent injection as compared to about 0.7% for baseline conditions.

5.4.2 Dust Electrical Resistivity and ESP Performance

The resistivity of the baseline fly ash measured in situ with about 23 ppm SO_3 naturally occurring in the flue gas from the medium sulphur eastern U.S. bituminous coal is about 10^8 ohm.cm. During the injection of all three sorbents, dust resistivities increased consistently about three to four orders of magnitude to 10^{11}-10^{12} ohm.cm. This seriously degraded the electrical operation and collection efficiency of the experimental ESP. The results are summarized in Table 9.

The dust loading to the CRF ESP with sorbent injection increased 2 to 3 fold from a baseline level of about 1.4 g/m^3. This resulted in reduced collection efficiency thereby causing a 2 to 3 fold increase in dust emission for limestone. The waste from hydrated lime injection ashes was very "sticky" and difficult to remove from the ESP and some sparking was observed. Dust emissions increased by a factor of 7 from baseline level of 0.15 g/m^3. Since the pilot scale ESP is of a simple design and cannot closely simulate full scale precipitator operation, the dust emission and ESP efficiencies should be regarded as a relative trend rather than an absolute value.

Humidification of FSI flue gases was also carried out in order to capture extra SO_2, reduce ash resistivity and improve ESP performance. The humidification was carried out on a waste produced by the injection of: a) Beachville limestone while burning a 1.7% S eastern US bituminous coal and a 1.4% S W Canadian - US Coal blend and b) hydrated lime and dolomite with the US coal. The humidification was carried out under optimized operating conditions as described in Section 5.4.

TABLE 9

COMPARISON OF SORBENT INJECTION WASTES

RUN	COAL	SORBENT	IN-FURNACE INJECTION			HUMIDIFICATION SO_2 CAPT %	TOTAL SO_2 CAPT %	WASTE COMPOSITION, g/kg							Kg WASTE/ 100kg COAL (ESTIMATED)	ASH RESISTIVITY ohm.cm	DUST LOADING g/m^3		COLLECTION EFFICIENCY %
			INJ. TEMP °C	Ca/S RATIO	SO_2 CAPT %			CaO	$CaSO_4$	$CaCO_3$	MgO	$Ca(OH)_2$	LOI	CARBON IN ASH			BEFORE	AFTER	
CRF BASE LINE								34	39		9		47	31	8.8	8.3×10^{7}	1.4	0.15	89
LVO42	US																		
CRF		Limestone	1100	3.0	41			337	150	30			108	95	18	1.1×10^{11}	3.4	0.43	87
CRF		Limestone	1100	3.0	43	18	61									2.3×10^{8}	+1.7	0.35	79
LVHL19	US																		
CRF		Hydrated Lime	875	2.5	65			268	256	61	7	51	174	48	19	2.7×10^{12}	4.0	1.1	73
CRF		Hydrated Lime	875	2.5	65	1.6	67									1.4×10^{8}	2.9	0.62	79
LVOJECK	US																		
CRF		Dolomite	1100	2.5	44			221	245	67	128		179	69		2.8×10^{10}	1.8	0.13	93
CRF		Dolomite	1100		44	7													
CRF	US-W Cdn Blend	Limestone	1100	3.0	46		51									2.8×10^{11}	2.5	0.3	87
		Limestone	1100	3.0	46	11.3	57									1.8×10^{8}	2.4	0.075	97
Lakeview TGS composite sample from east-west hoppers		Limestone	1250	3.1	43			265	111	48				101	15	5×10^{13}			
Lakeview TGS composite sample from east-west hoppers		Hydrated Lime	1250	2.8	49			206	77	85			165	119	18	1.2×10^{13}	10.8*	0.19	98

* Inlet Loading 5.1 g/m^3)
Outlet Loading = 0.035 g/m^3)Baseline
Efficiency = 99.3%)

+ with humidification some in-probe fallout was observed

Humidification in all these cases reduced resistivity by 3 to 4 orders of magnitude from a range of 2.7×10^{12} - 1.1×10^{11} to 1.4 to 2.3×10^{8} ohm cm. This resulted in improved ESP collection efficiency and reduced particulate emissions at the CRF (see Table 9).

6.0 SUMMARY AND CONCLUSIONS

A. Sulphur Capture by Various Sorbents

The effect of operating variables on sulphur capture by in-furnace injection of calcium-based sorbents has been studied at Ontario Hydro's 640 MJ/h Combustion Research Facility, under conditions simulating full scale operation while burning a high volatile 1.7% sulphur eastern US bituminous coal and a 1.4% sulphur 50-50 Western Canadian - US Coal blend.

The results of the study are summarized below:

- One of the most important parameters determining the degree of sulphur capture achievable by dry sorbent injection is the type of sorbent used. Hydrated lime is superior to limestone; sulphur capture by pressure hydrated lime is similar to that of hydrated lime. Dolomitic stone is better than calcitic limestone on a calcium basis, but not on the total mass basis due to the inert magnesium.

- Other parameters found to affect sorbent performance include sorbent surface area, porosity and addition rate (Ca/S ratio), injection temperature and residence time in the sulphation window. Optimum operating conditions simulating a typical Ontario Hydro boiler are: injection temperature of 1100°C, Ca/S ratio of 2.5-3 and residence time 600 ms. Under these conditions sulphur capture by hydrated lime, limestone and dolomitic stone are 63%, 43% and 51%. Corresponding sorbent utilizations are 25%, 14% and 17%.

- A statistical model has been developed to describe sulphur capture by calcium based sorbent injection as a function of operating variables under conditions simulating Ontario Hydro's full scale units considered for the application of this technology. The prediction of the model agrees well with full scale test data, indicating that the model is useful for predicting sorbent performance at full scale boilers.

- Humidification of furnace sorbent injection waste produced maximum incremental SO_2 capture of about 6% for hydrated lime, 18% for limestone and 7% for dolomite bringing the total SO_2 capture to 67%, 61% and 51%. Corresponding sorbent utilizations are 27% for hydrated lime, 20% for limestone and 20% for dolomite.

- The process produces a waste which is finer and about two times as much as the baseline ash. CaO, $CaSO_4$ and $CaCO_3$ content of the ash ranges between 206-337, 77-256 and 30-85 g/kg respectively, depending on front end conditions.

- Ash resistivities were up by about three to four orders of magnitude from a baseline level of 10^8 to 10^{11}-10^{12} ohm.cm. Dust loading to the pilot ESP increased by 2 to 3 fold with sorbent injection. This caused an increase of 2 - 3 fold in dust emission level dropping collection efficiency by 2 to 16%.

- Slagging does not appear to be a problem and the soft deposit formed on the furnace walls and heat exchanger surfaces was easily removable. Carbon content of the waste is higher than that of the baseline ash. The higher levels of carbon together with the finer waste and higher calcium content is expected to pose difficult problems in handling and disposal.

B. **Humidification**

- SO_2 capture in the humidifier is a sensitive function of the operating conditions (water droplet size, approach to adiabatic saturation and residence time) and the origin of the waste.

- Under optimized operating conditions humidification of sorbent injection flue gases to a 20-25°F approach to adiabatic saturation produced an incremental SO_2 capture of about 18% for Beachville limestone, 7% for dolomite and 6% for hydrated lime bringing the total SO_2 capture to 61%, 51% and 67%, respectively. For the 50-50 W. Canadian - U.S. Coal blend incremental SO_2 capture with Beachville limestone is 11% bringing the total SO_2 removal to 57%.

- Ash resistivities were lowered by 3 to 4 orders of magnitude from a range of 10^{12} - 10^{11} ohm.cm to about 10^8 ohm.cm. This reduced particulate emissions at the CRF by about 2 to 4 fold and improved the collection efficiency of the ESP.

7.0 RECOMMENDATIONS

Further work is recommended:

- To elucidate the mechanism and determine the rate of reaction between calcium oxide containing wastes and SO_2 in the flue gases in the presence of moisture. To develop a sulphation model capable of describing the process under full scale operating conditions.
- To evaluate the efficiency of the two stage humidification on the pilot scale and the effect of operating parameters.
- To study waste activation and recycling to activate unreacted CaO for additional SO_2 capture and better sorbent utilization.

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